

# L'anti-matière au service de l'imagerie médicale

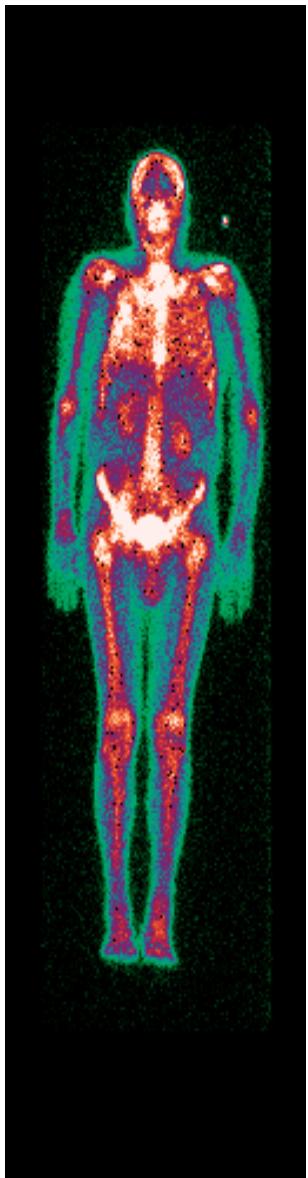
Pr Christian MOREL

Centre de Physique des Particules de Marseille



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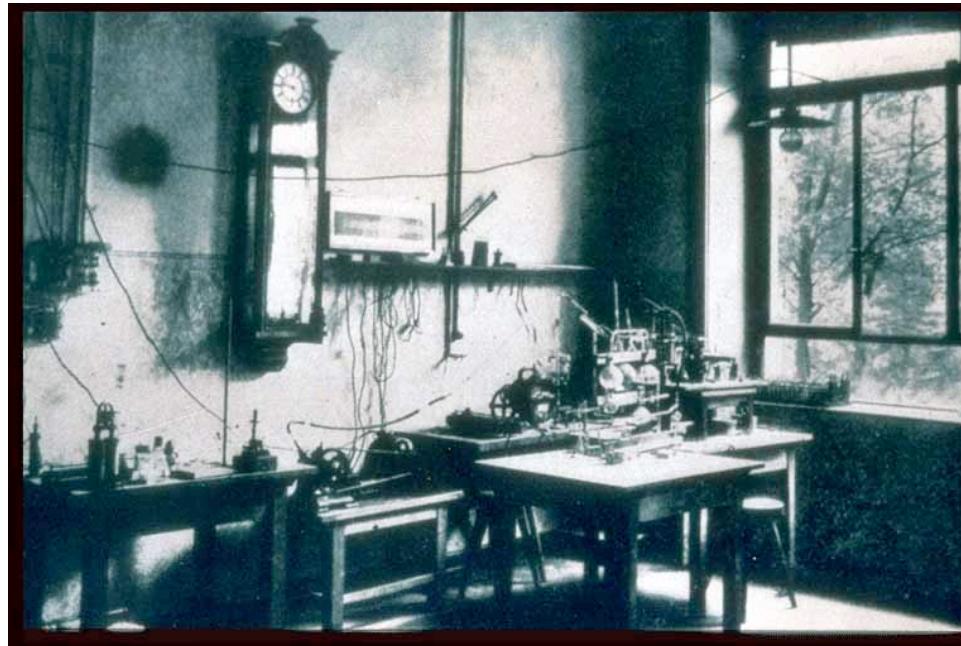




- 1895: **Rayons X** (W. Roentgen, Würzburg)  
Prix Nobel 1901
- 1896: **Radioactivité** (H. Becquerel, Paris)  
Prix Nobel 1903
- 1897: **Electron** (J.J. Thomson, Cambridge)  
Prix Nobel 1906
- 1898: **Radium et Polonium** (Pierre et Marie Curie, Paris)  
Prix Nobel 1903, 1911
- 1899: **Rayons alpha et beta** (E. Rutherford, Cambridge)  
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- 1931: **Cyclotron** (E. Lawrence, Berkeley)  
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- 1932: **Neutron** (J. Chadwick, Cambridge)  
Prix Nobel 1935
- 1930: Théorie des trous (P.A.M. Dirac, Cambridge)  
Prix Nobel 1933
- 1932: **Positron** (C.D. Anderson, Berkeley)  
Prix Nobel 1936

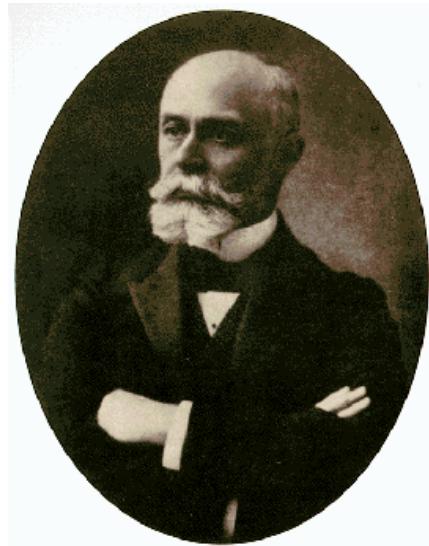


1895:  
Découverte des rayons X  
par W. Roentgen à  
l'Université de Würzburg

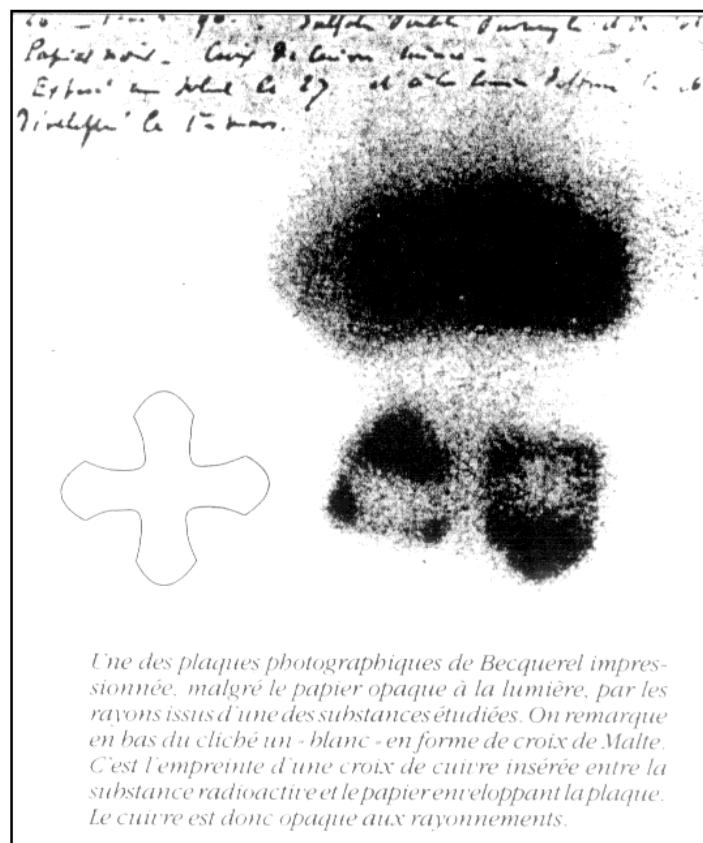


1895: Rayons X (W. Roentgen, Würzburg)  
Prix Nobel 1901





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Prix Nobel 1901
- 1896: Radioactivité (H. Becquerel, Paris)  
Prix Nobel 1903



Une des plaques photographiques de Becquerel impressionnée, malgré le papier opaque à la lumière, par les rayons issus d'une des substances étudiées. On remarque en bas du cliché un - blanc - en forme de croix de Malte. C'est l'empreinte d'une croix de cuivre insérée entre la substance radioactive et le papier enveloppant la plaque. Le cuivre est donc opaque aux rayonnements.



1895: Rayons X (W. Roentgen, Würzburg)

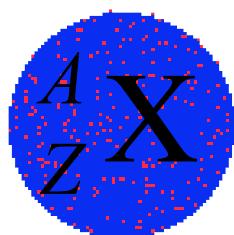
# Prix Nobel 1901

1896: Radioactivité (H. Becquerel, Paris)

# Prix Nobel 1903

1897: Electron (J.J. Thomson, Cambridge)

# Prix Nobel 1906



1895: Rayons X (W. Roentgen, Würzburg)

Prix Nobel 1901

1896: Radioactivité (H. Becquerel, Paris)

Prix Nobel 1903

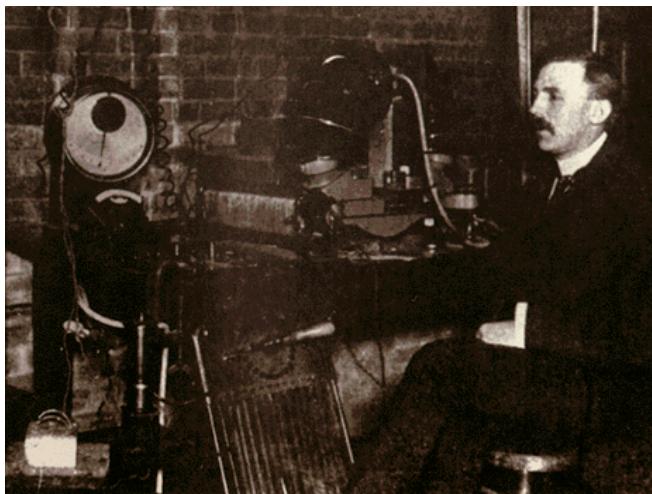
Los Alamos National Laboratory Chemistry Division

## Periodic Table of the Elements

element names in blue are liquids at room temperature  
element names in red are gases at room temperature  
element names in black are solids at room temperature



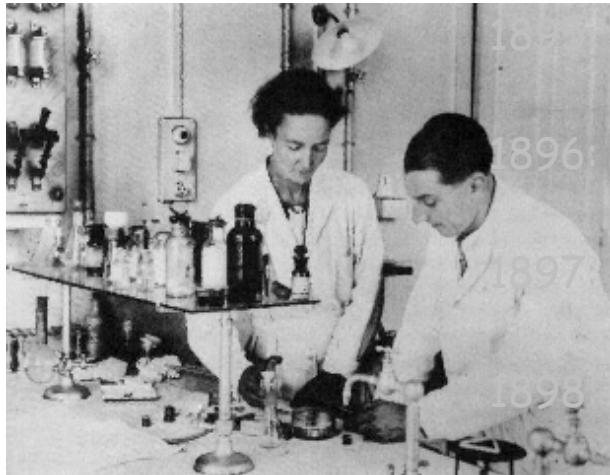
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- 1899: **Rayons alpha et beta** (E. Rutherford, Cambridge)  
Prix Nobel 1908



rayons  $\alpha$ : très peu pénétrants  $\sim m_{He^{++}}$  (1908)

rayons  $\beta$ : plus pénétrants  $\sim$  électrons (1902)

rayons  $\gamma$ : très pénétrants  $\sim$  photons (1900)



1895:

1896:

1897:

1898:

1899:

1911:

1932:



Rayons X (W. Roentgen, Würzburg)

Prix Nobel 1901

Radioactivité (H. Becquerel, Paris)

Prix Nobel 1903

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Radium et Polonium (Pierre et Marie Curie, Paris)

Prix Nobel 1903, 1911

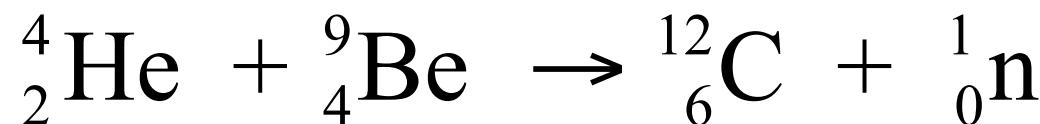
Rayons alpha et beta (E. Rutherford, Cambridge)

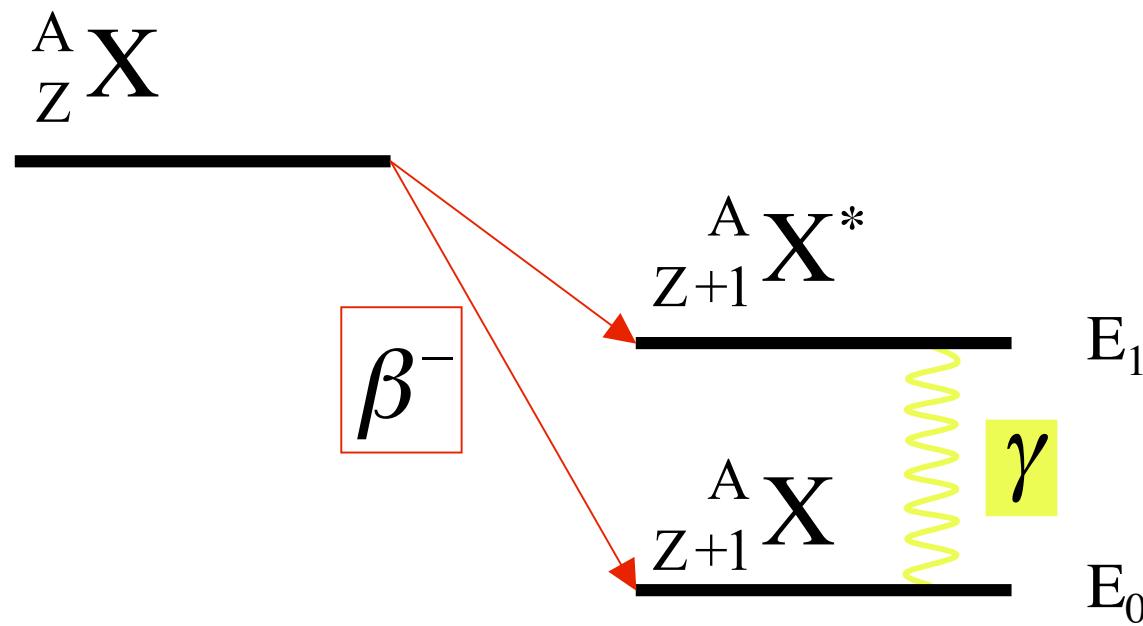
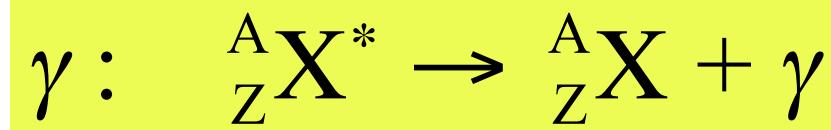
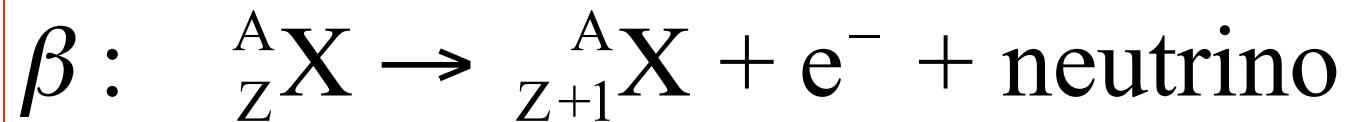
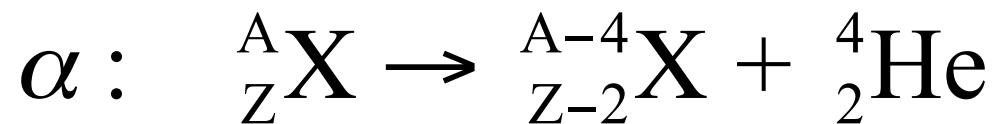
Prix Nobel 1908

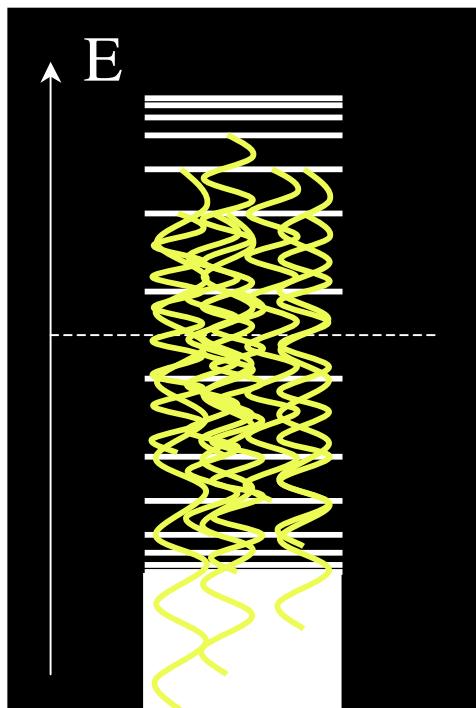
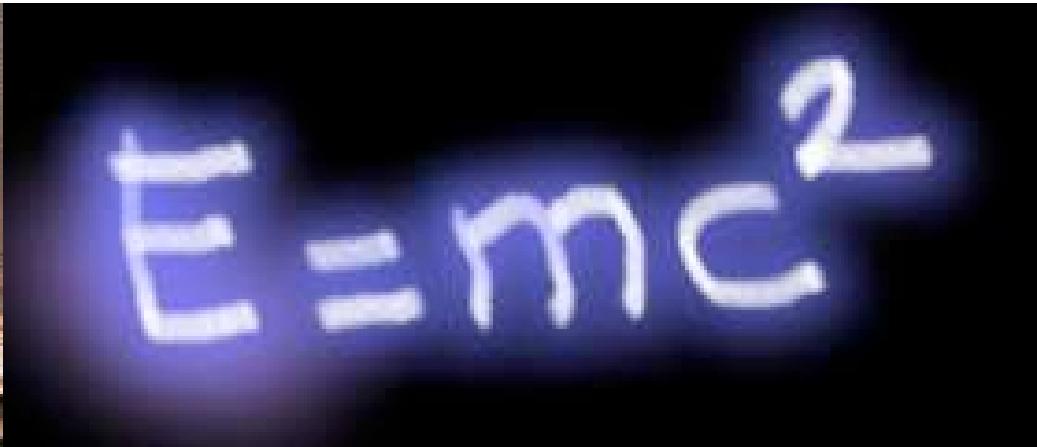
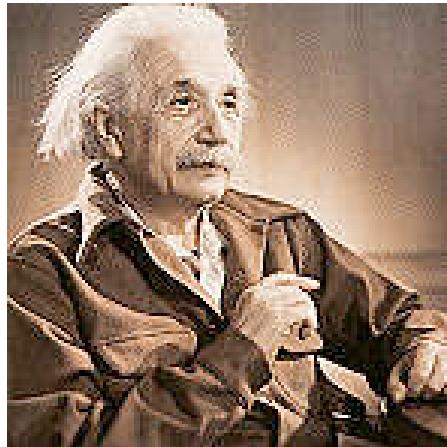
Noyau (E. Rutherford, Cambridge)

**Neutron** (J. Chadwick, Cambridge)

Prix Nobel 1935



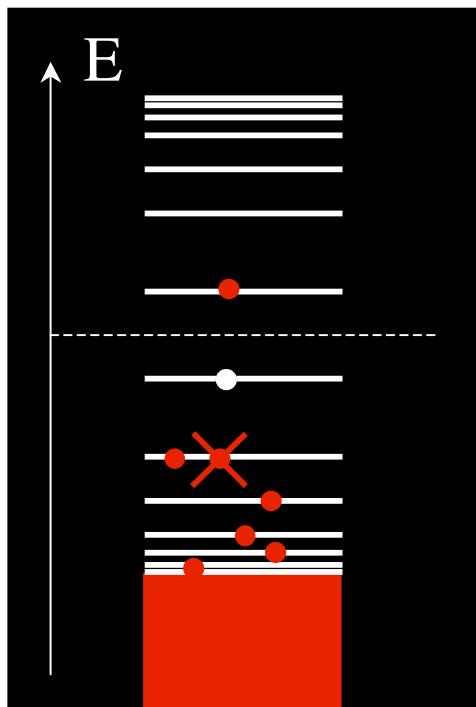
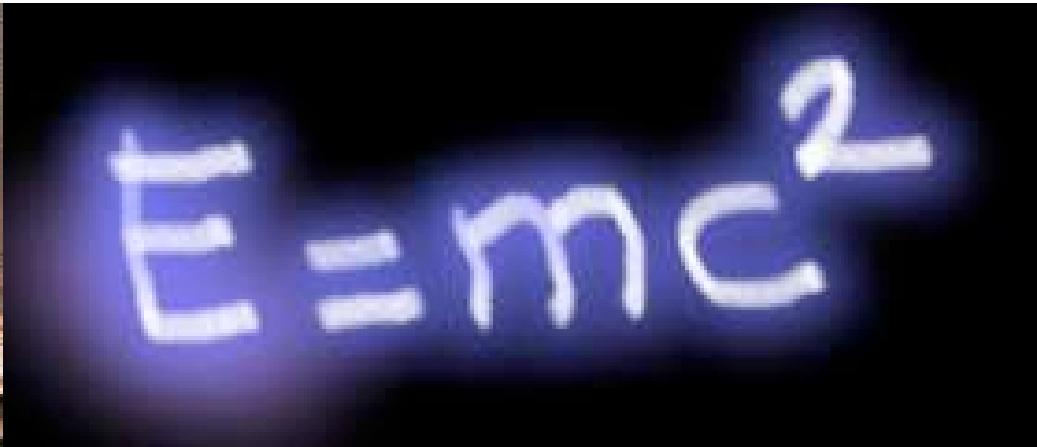
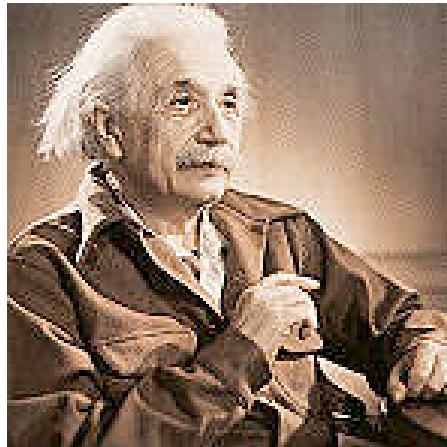




$$E^2 = (mc^2)^2 + (pc)^2$$

$$E = +\sqrt{(mc^2)^2 + (pc)^2}$$

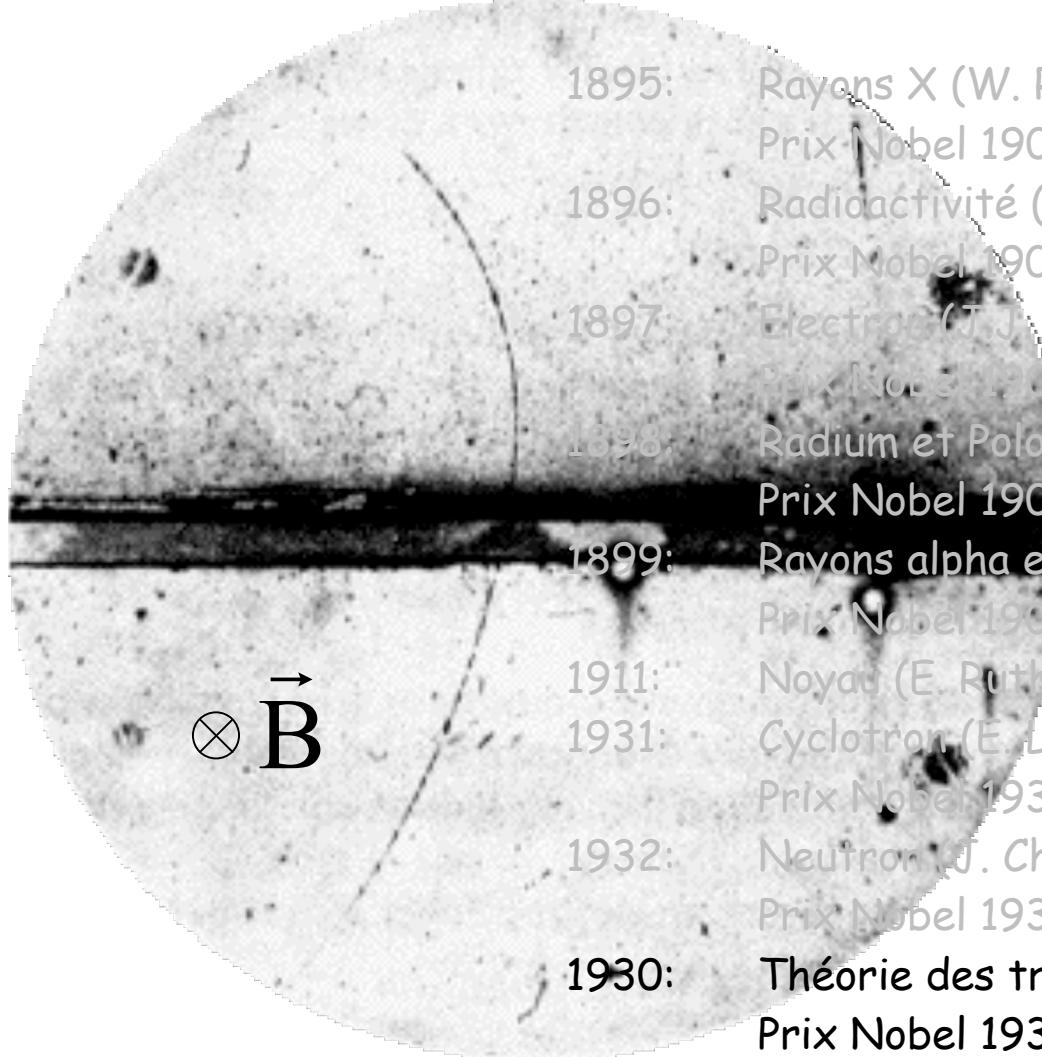
$$E = -\sqrt{(mc^2)^2 + (pc)^2}$$



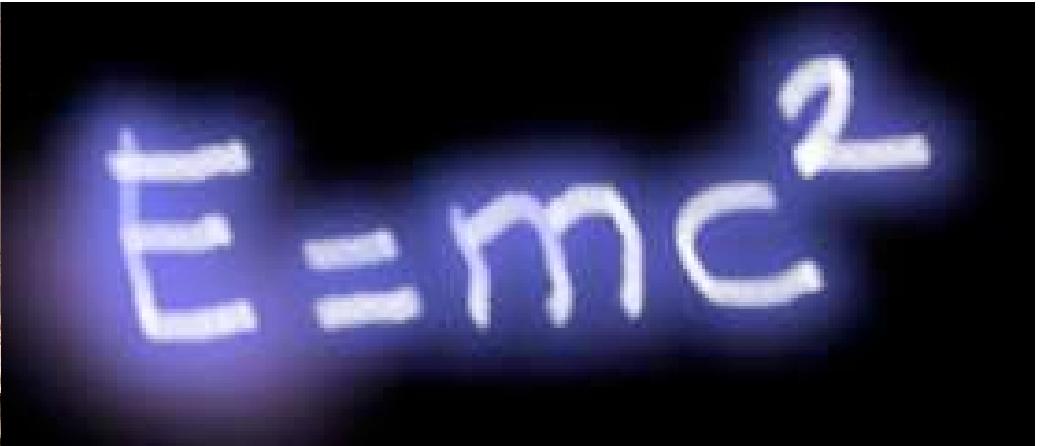
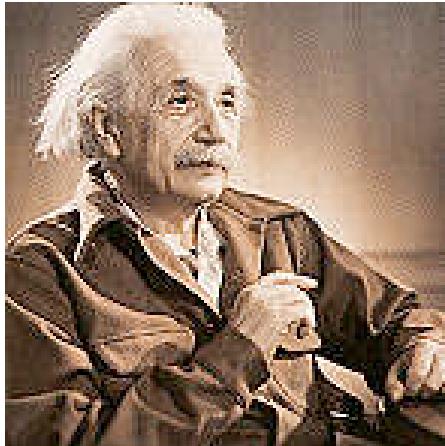
$$E^2 = (mc^2)^2 + (pc)^2$$

Trou d'énergie négative = électron positif  
d'énergie positive

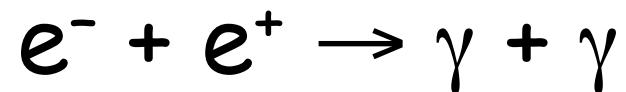
positon (ou positron  $e^+$ ) = particule d'anti-matière  
de l'électron ou  
anti-électron



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Prix Nobel 1933
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Prix Nobel 1936



## Diffusion Compton

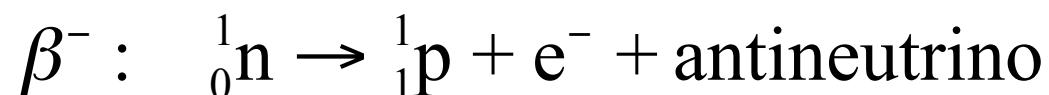
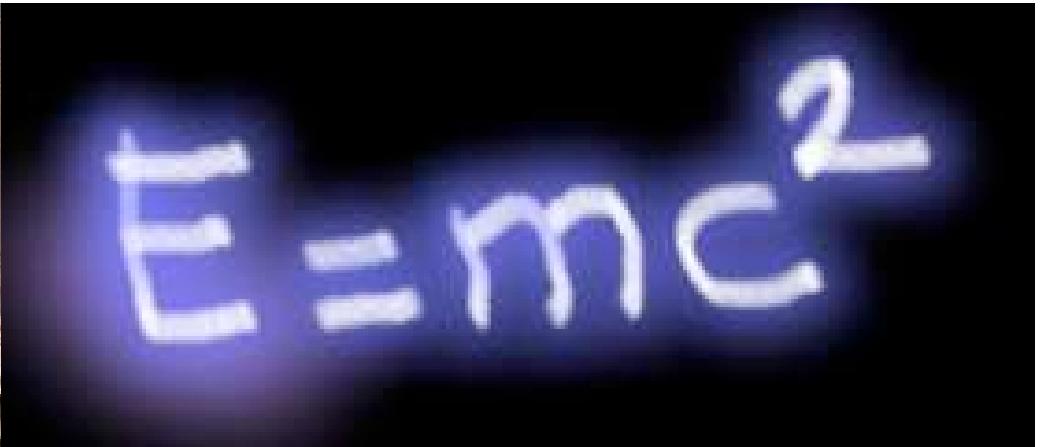
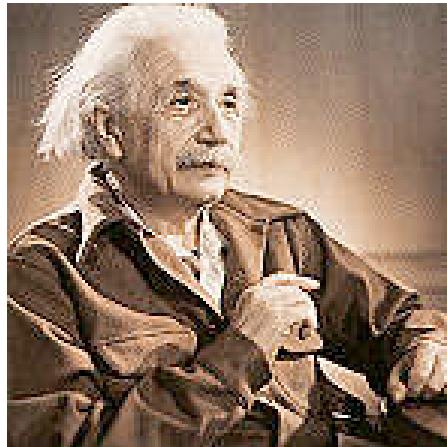


## Annihilation matière anti-matière



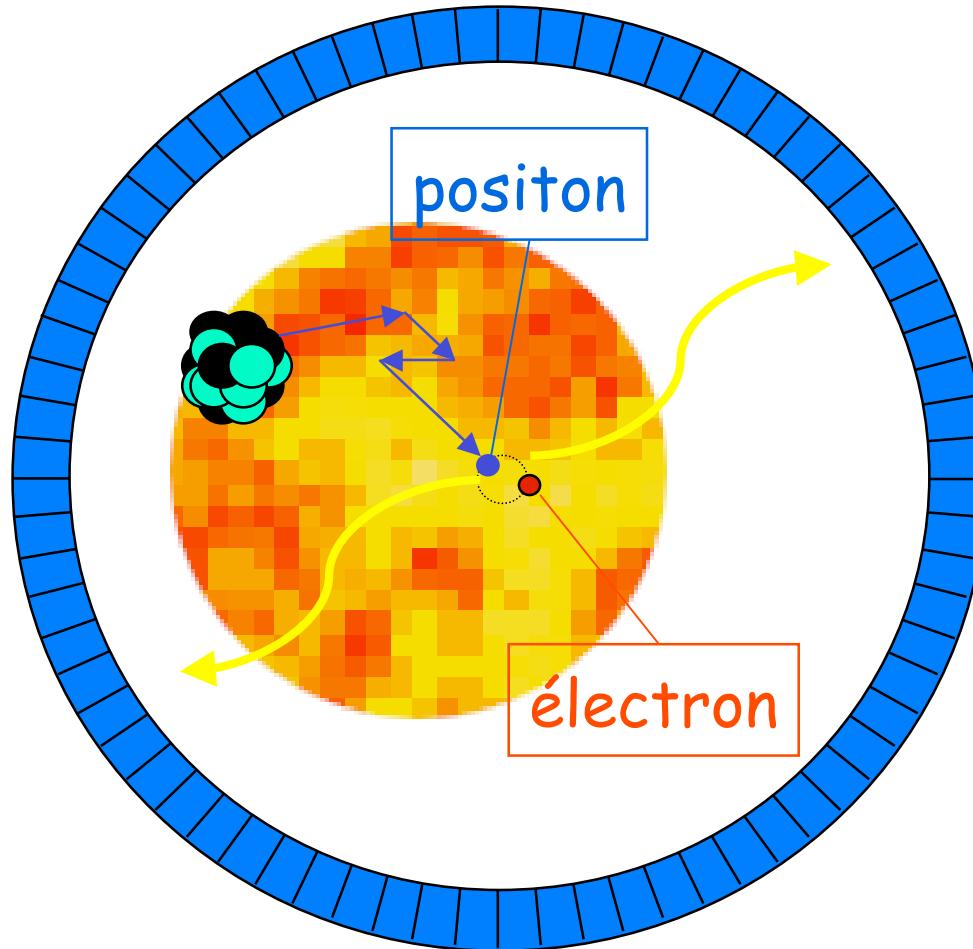
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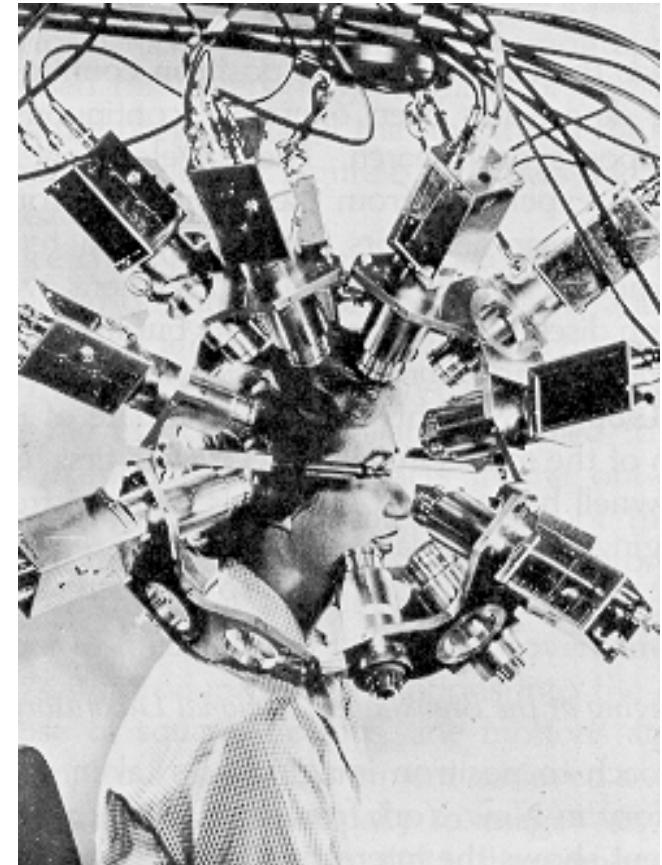
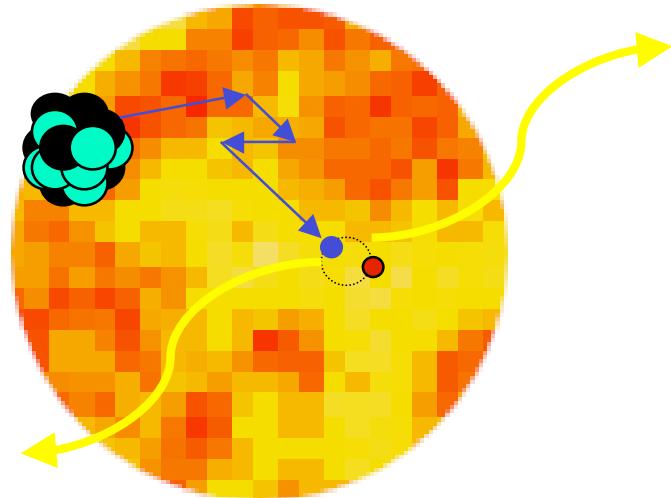


# Tomographie par Emission de Positons (TEP)

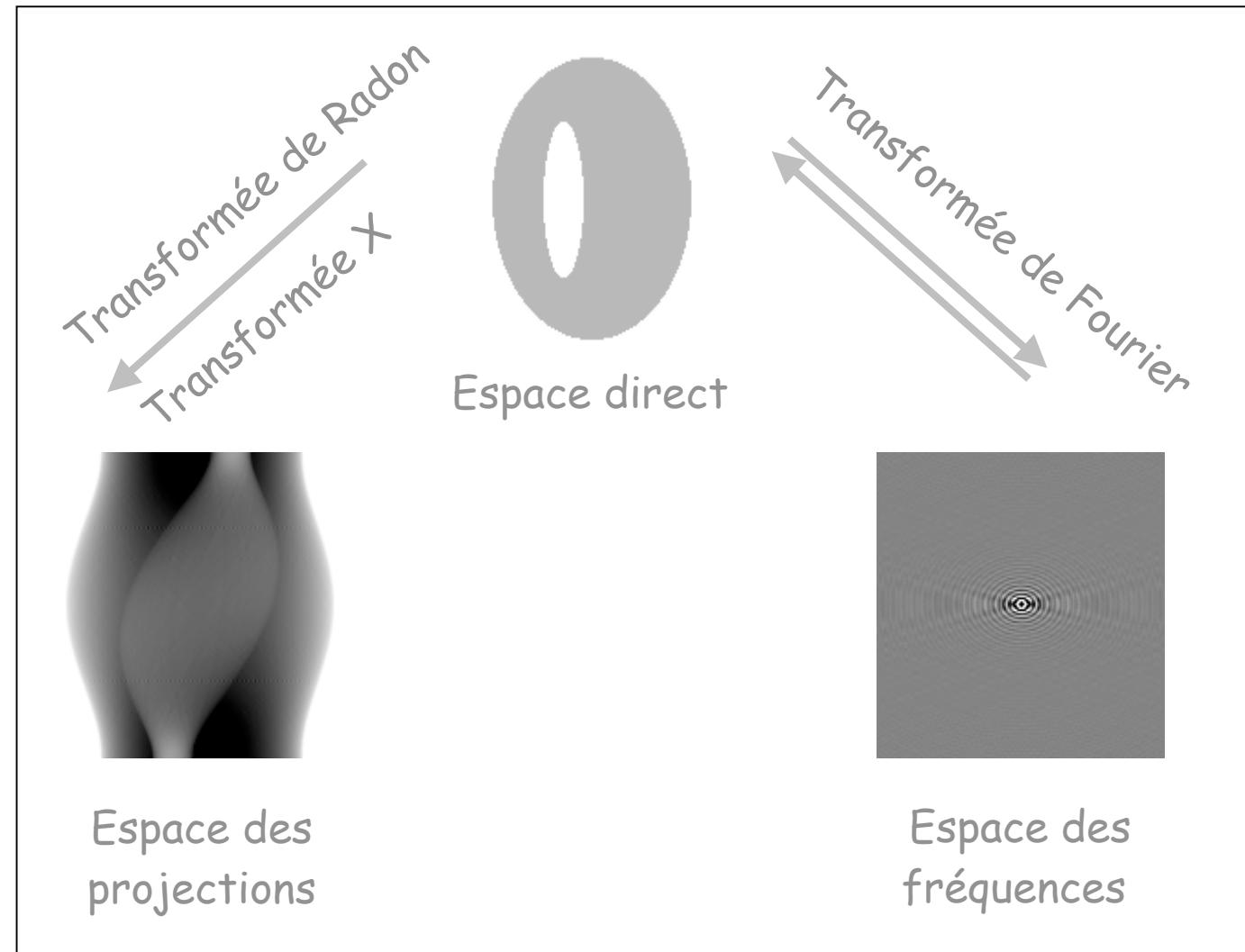
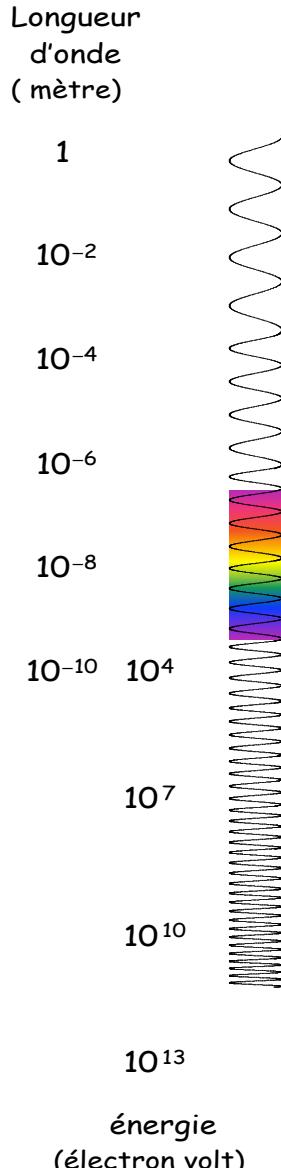
$^{18}\text{F}$   
 $^{11}\text{C}$   
 $^{13}\text{N}$   
 $^{15}\text{O}$   
 $^{68}\text{Ga}$



# Tomographie par émission de positons (TEP)

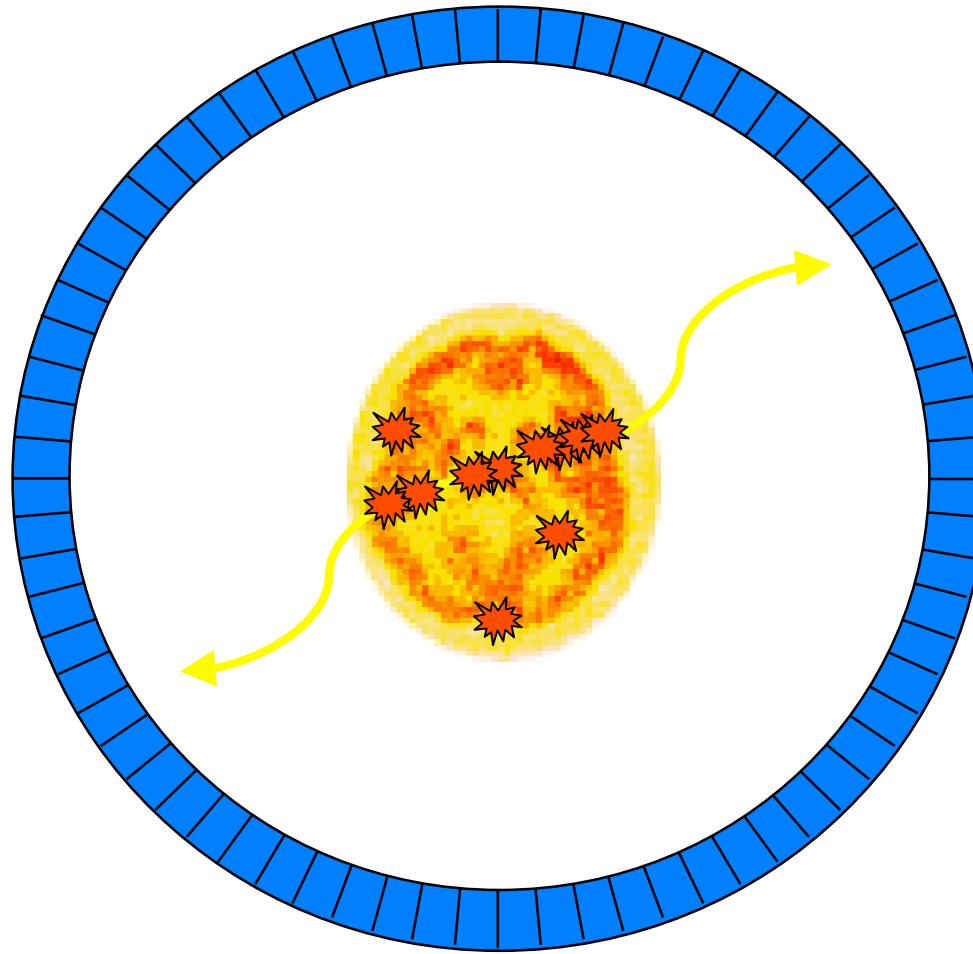


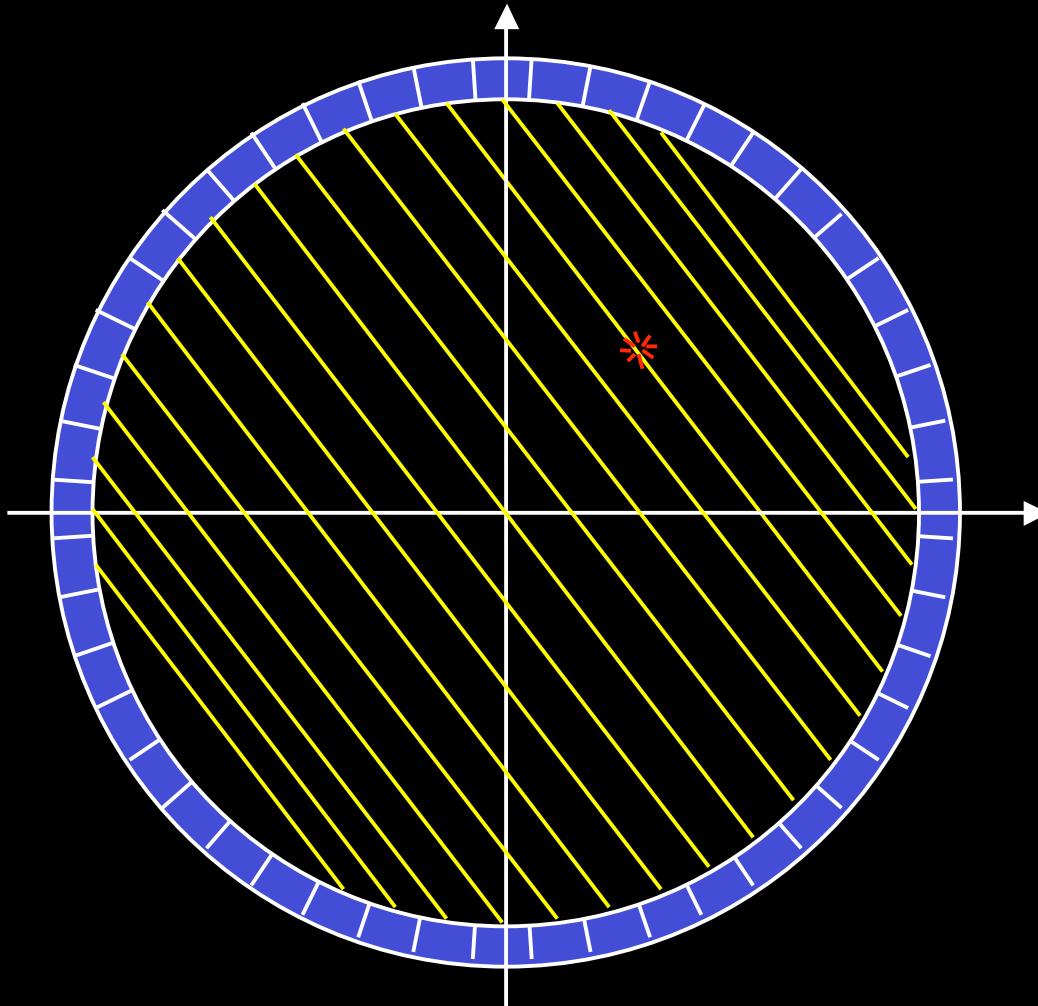
1951: The use of positron emitting radioisotopes for the localization of brain tumours *Science* **113** 525 (Wrenn *et al.*, Duke)

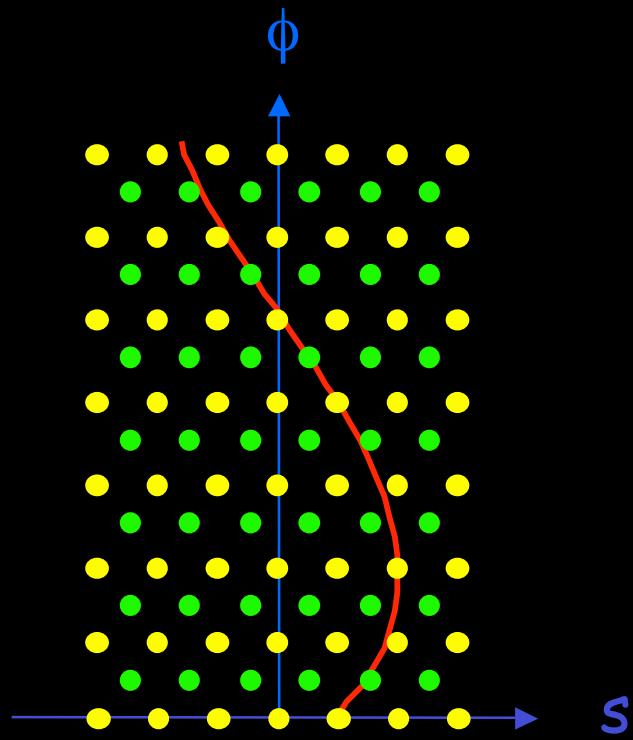
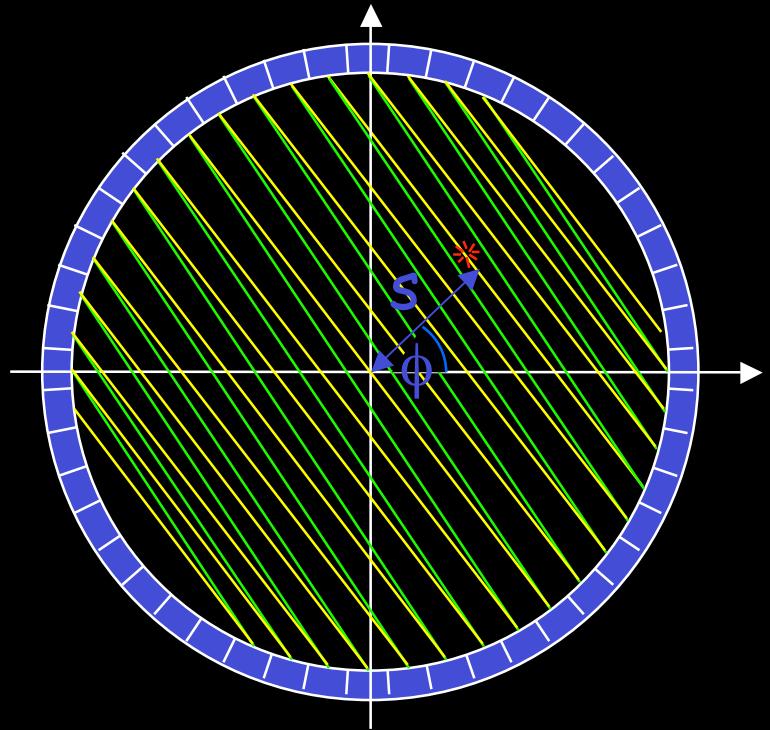


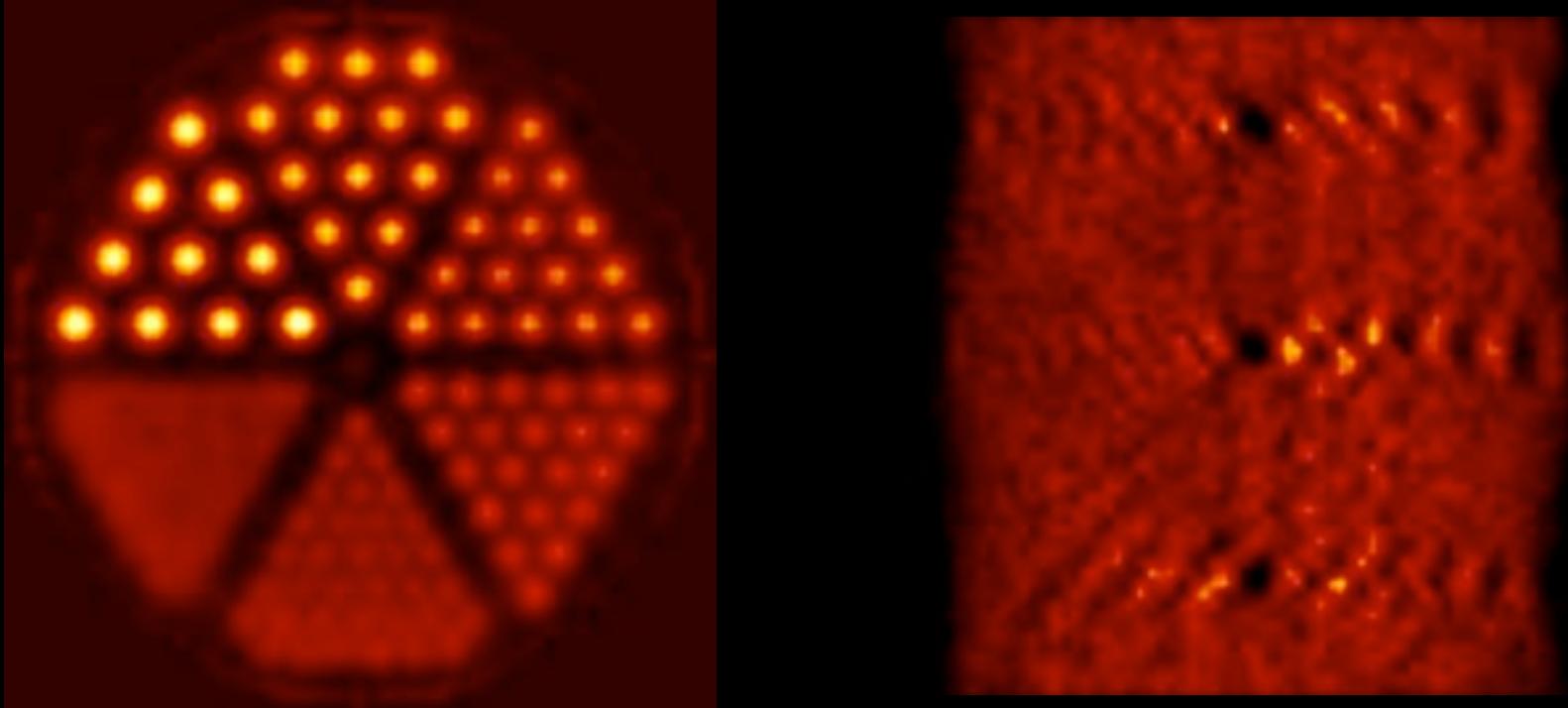
# Tomographie par Emission de Positons (TEP)

$^{18}\text{F}$   
 $^{11}\text{C}$   
 $^{13}\text{N}$   
 $^{15}\text{O}$   
 $^{68}\text{Ga}$

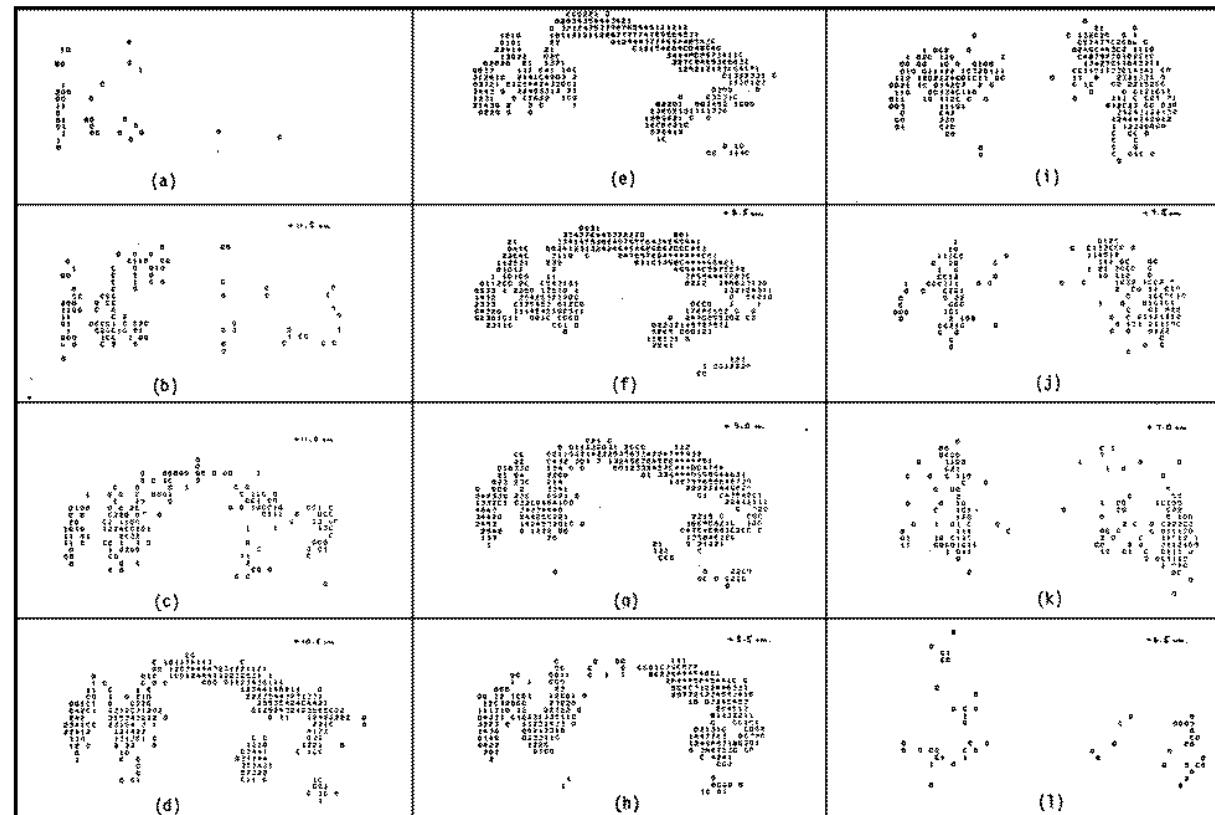
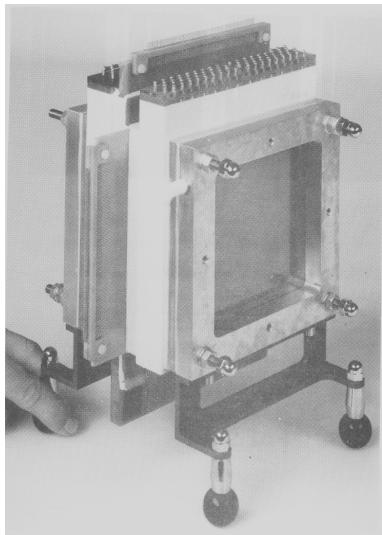








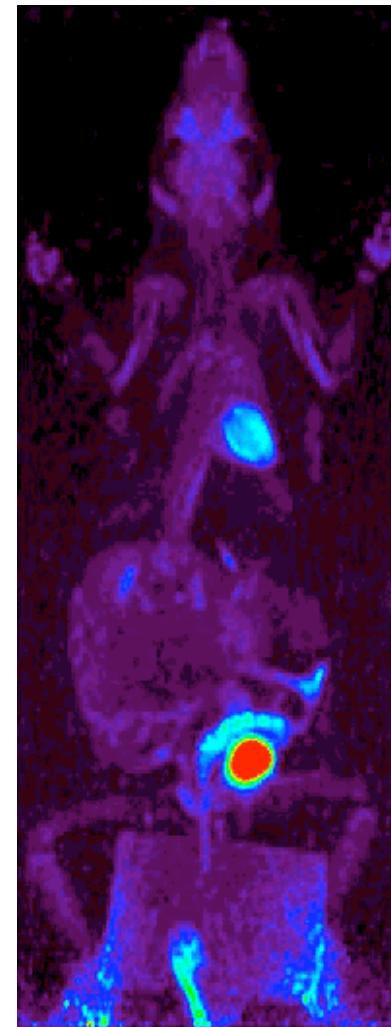
# 1978: High Density Avalanche Chamber (HiDAC) (Jeavons, Townsend, CERN)



# Imagerie fonctionnelle moléculaire

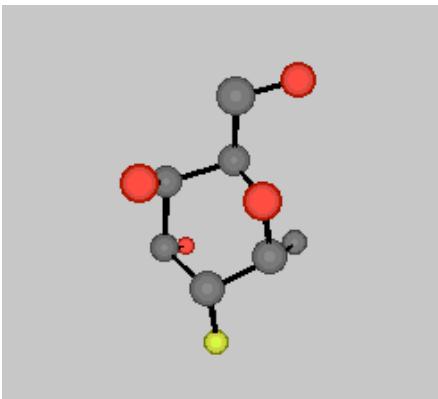


Quad-HiDAC  
Oxford Positron Systems

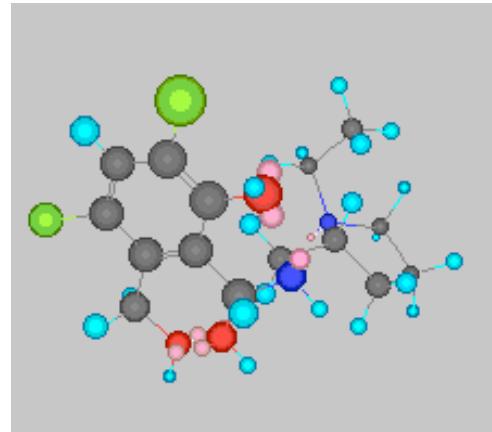


courtesy: Paul Scherrer Institute, Switzerland

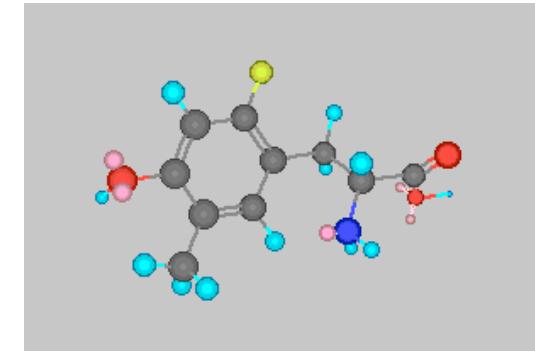
# Marquages radio-pharmaceutiques



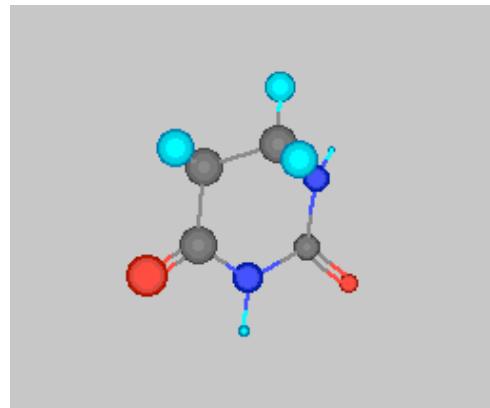
[<sup>18</sup>F]FDG



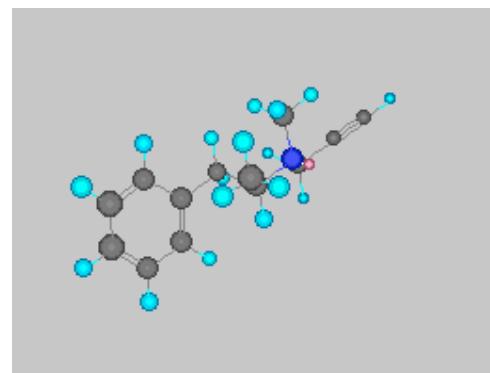
[<sup>11</sup>C]Raclopride



[<sup>18</sup>F]FluoroLDopa



[<sup>18</sup>F]Fluorouracil



[<sup>11</sup>C]L-deprenyl

$^{18}\text{F}$  (2 h)

$\text{H}_2^{18}\text{O}$  (p,n)  $^{18}\text{F}$

$^{20}\text{Ne}$  (d, $\alpha$ )  $^{18}\text{F}$

$^{11}\text{C}$  (20 min)

$^{14}\text{N}$  (p, $\alpha$ )  $^{11}\text{C}$



$^{13}\text{N}$  (10 min)

$^{12}\text{C}$  (d,n)  $^{13}\text{N}$

$^{13}\text{C}$  (p,n)  $^{13}\text{N}$

$\text{H}_2^{16}\text{O}$  (p, $\alpha$ )  $^{13}\text{N}$

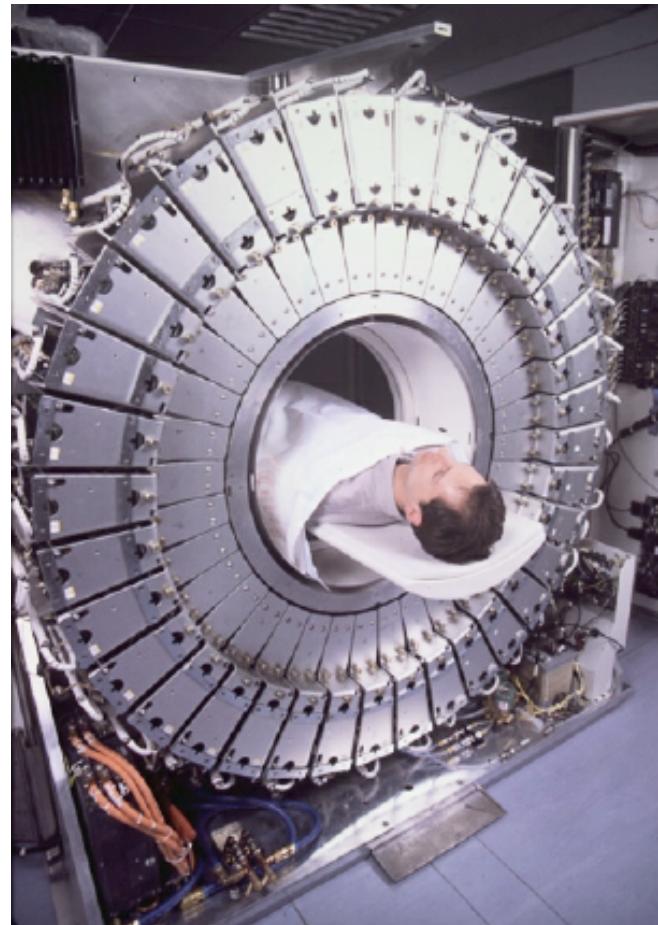
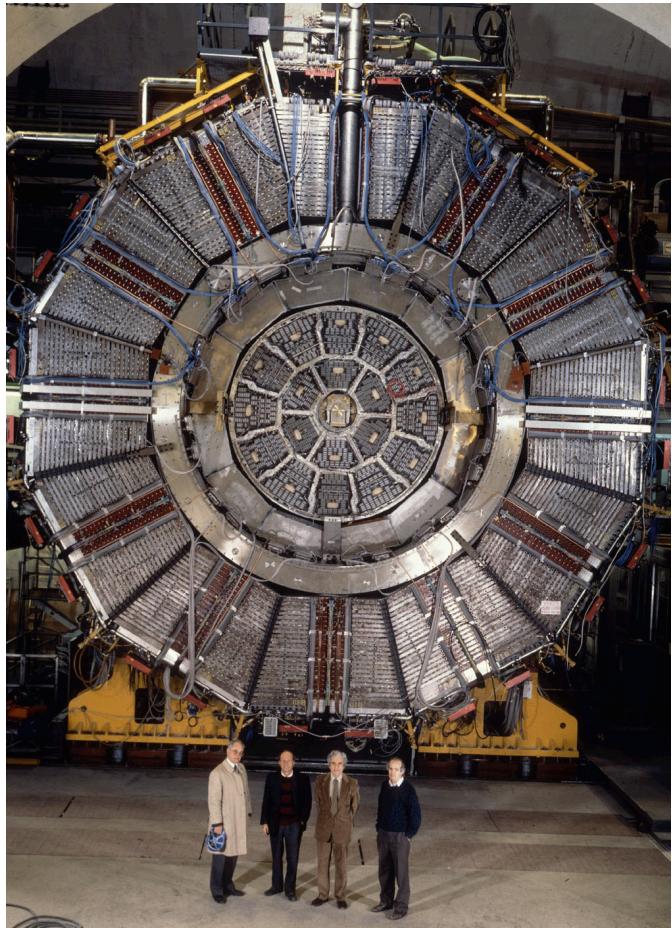
$^{15}\text{O}$  (2 min)

$^{14}\text{N}$  (d,n)  $^{15}\text{O}$

$^{15}\text{N}$  (p,n)  $^{15}\text{O}$



# Physique des particules appliquée à l'imagerie médicale



# Physique des particules appliquée à l'imagerie médicale

## Requirements for HEP EM calorimetry

- ✓ **Crystals** Technology transfer
  - High density ( $> 6 \text{ g/cm}^3$ )
  - Fast emission ( $< 100 \text{ ns}$ ), visible spectrum
  - Moderate to high light yield
  - High radiation resistance
- ✓ **Photodetectors** Technology transfer
  - Compact
  - High quantum efficiency and high gain
  - High stability
- ✓ **Readout electronics** Technology transfer
  - Fast shaping
  - Low noise
- ✓ **Software** Technology transfer
  - Handling of high quantity of data
- ✓ **General design** Technology transfer
  - Compact integration of a large number of channels ( $> 10'000$ )

## Requirements for Medical Imaging

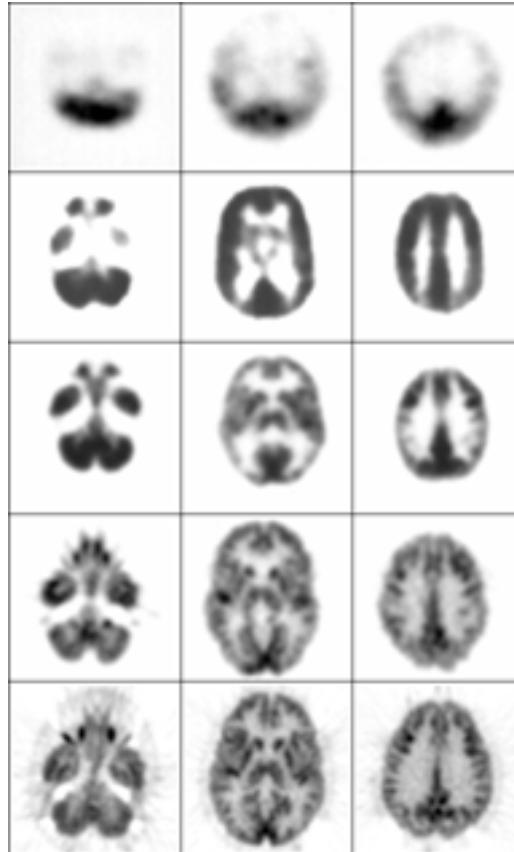
- ✓ **Crystals**
  - High density ( $> 7 \text{ g/cm}^3$ )
  - Fast emission ( $< 100 \text{ ns}$ ), visible spectrum
  - High light yield
  - Moderate radiation resistance
- ✓ **Photodetectors**
  - Compact
  - High quantum efficiency and high gain
  - High stability
- ✓ **Readout electronics**
  - Fast shaping
  - Low noise
- ✓ **Software**
  - Handling of high quantity of data
- ✓ **General design**
  - Compact integration of a large number of channels ( $> 10'000$ )



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# Instrumentation en constante évolution



PET III 1975

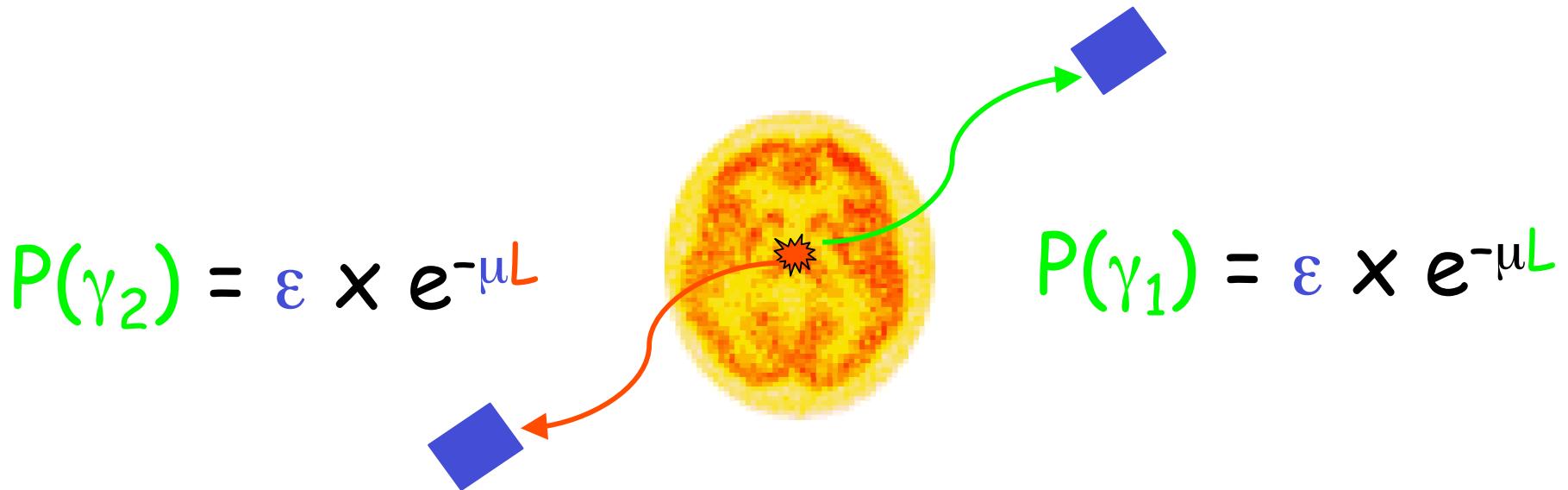
ECAT II 1977

NeuroECAT 1978

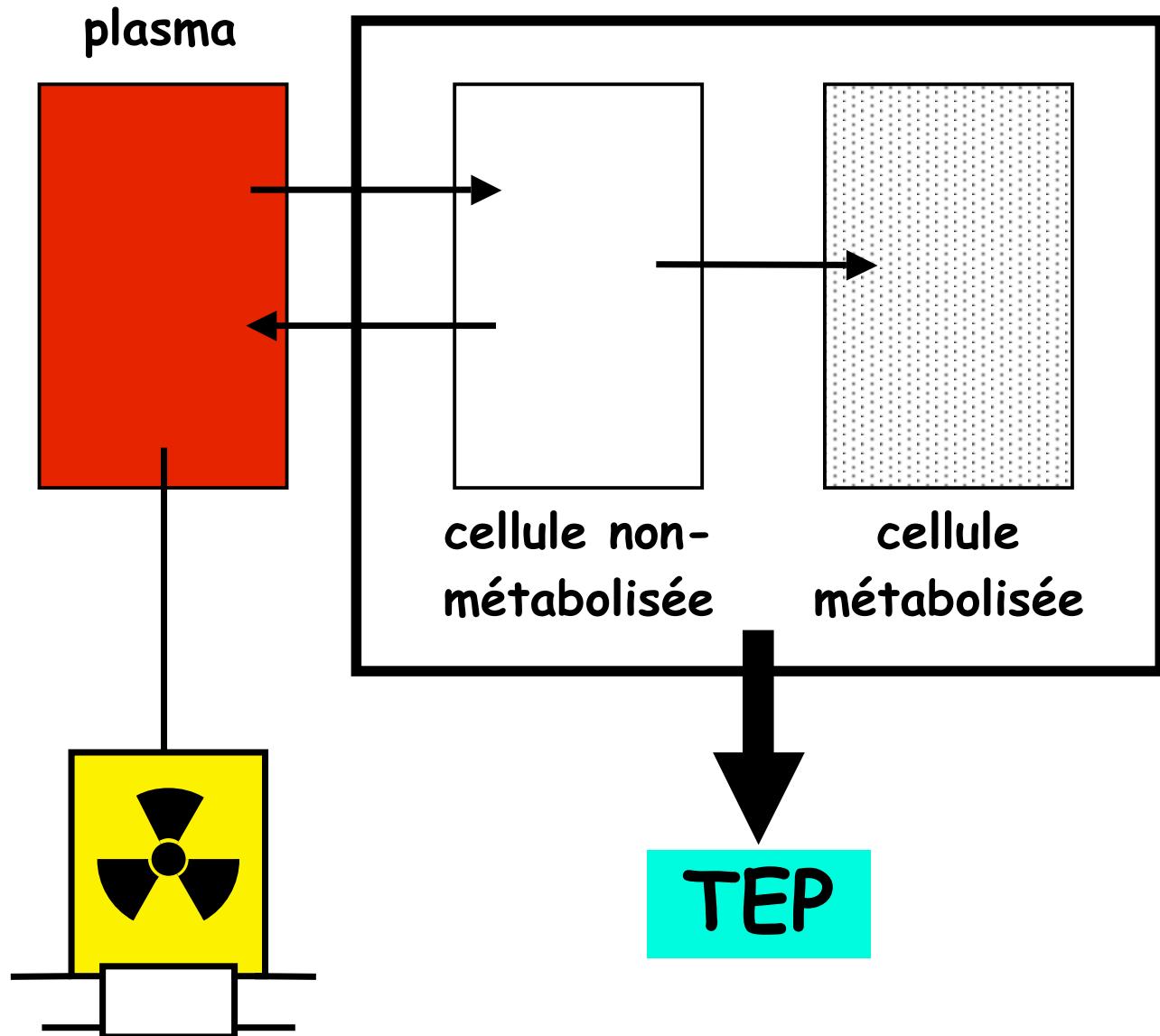
ECAT 931 1985

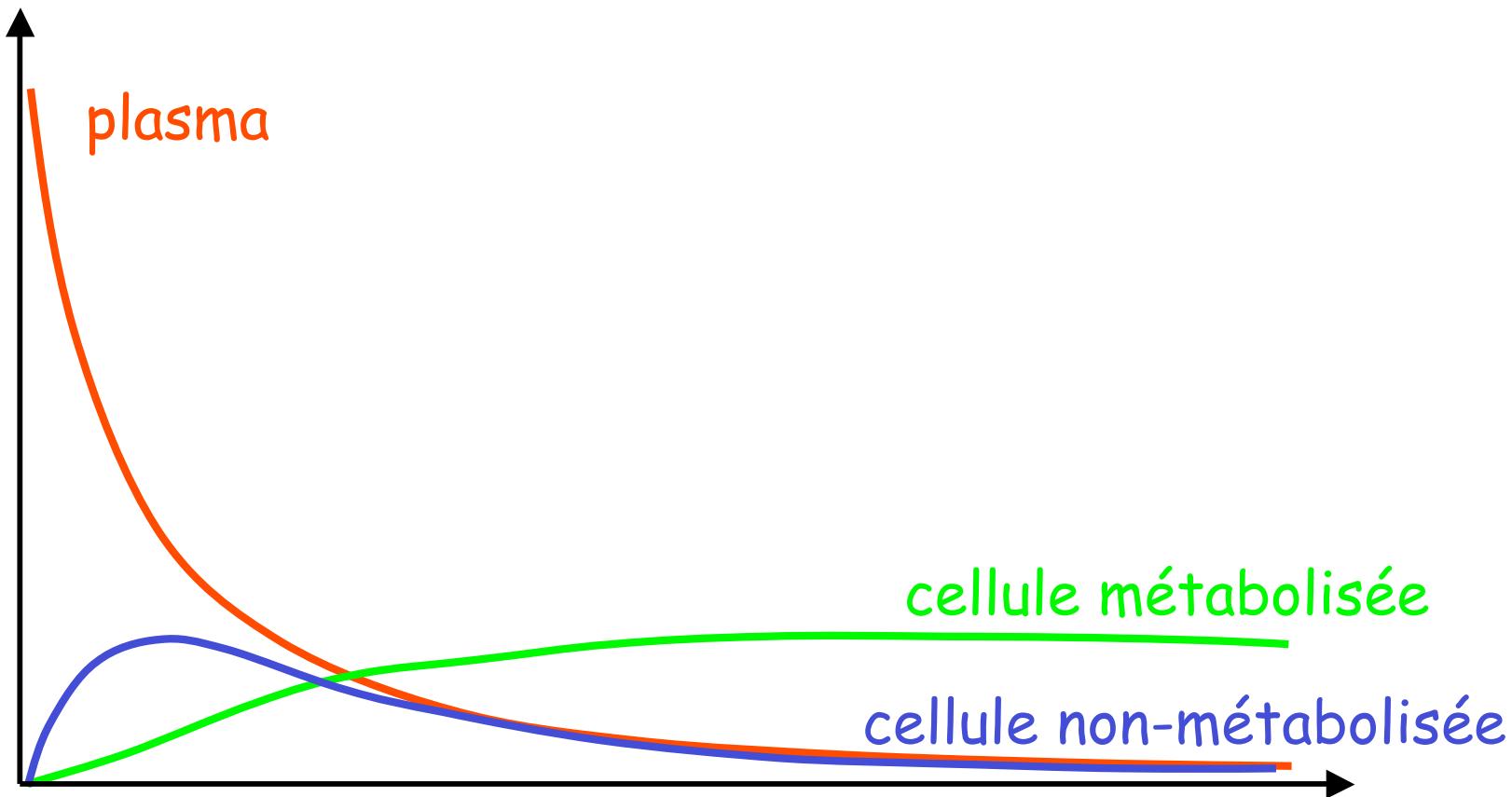
ECAT EXACT HR+ 1995

$$P(\gamma_1) \times P(\gamma_2) = \varepsilon^2 e^{-\mu(L+L)}$$

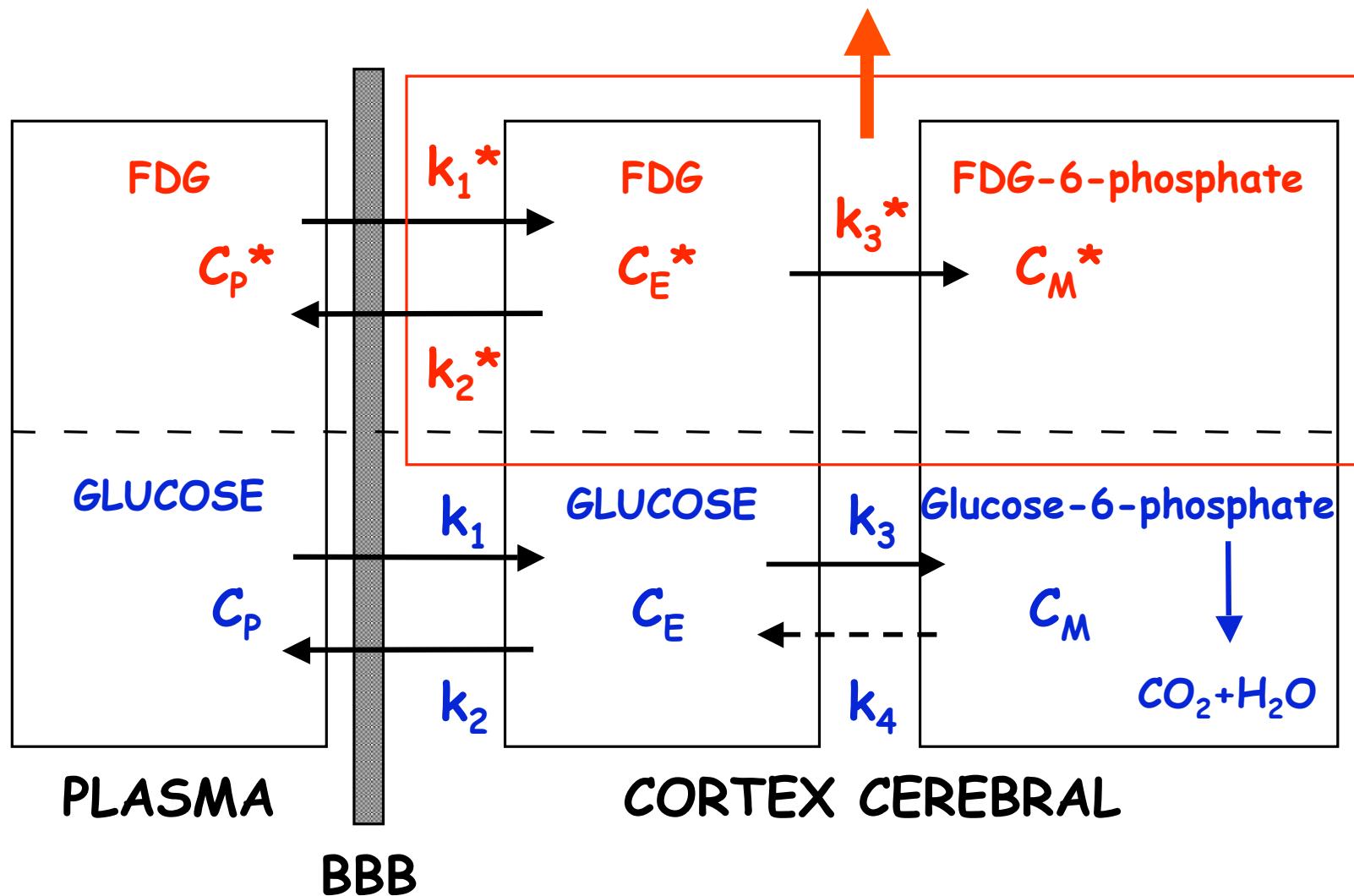


# Quantitation





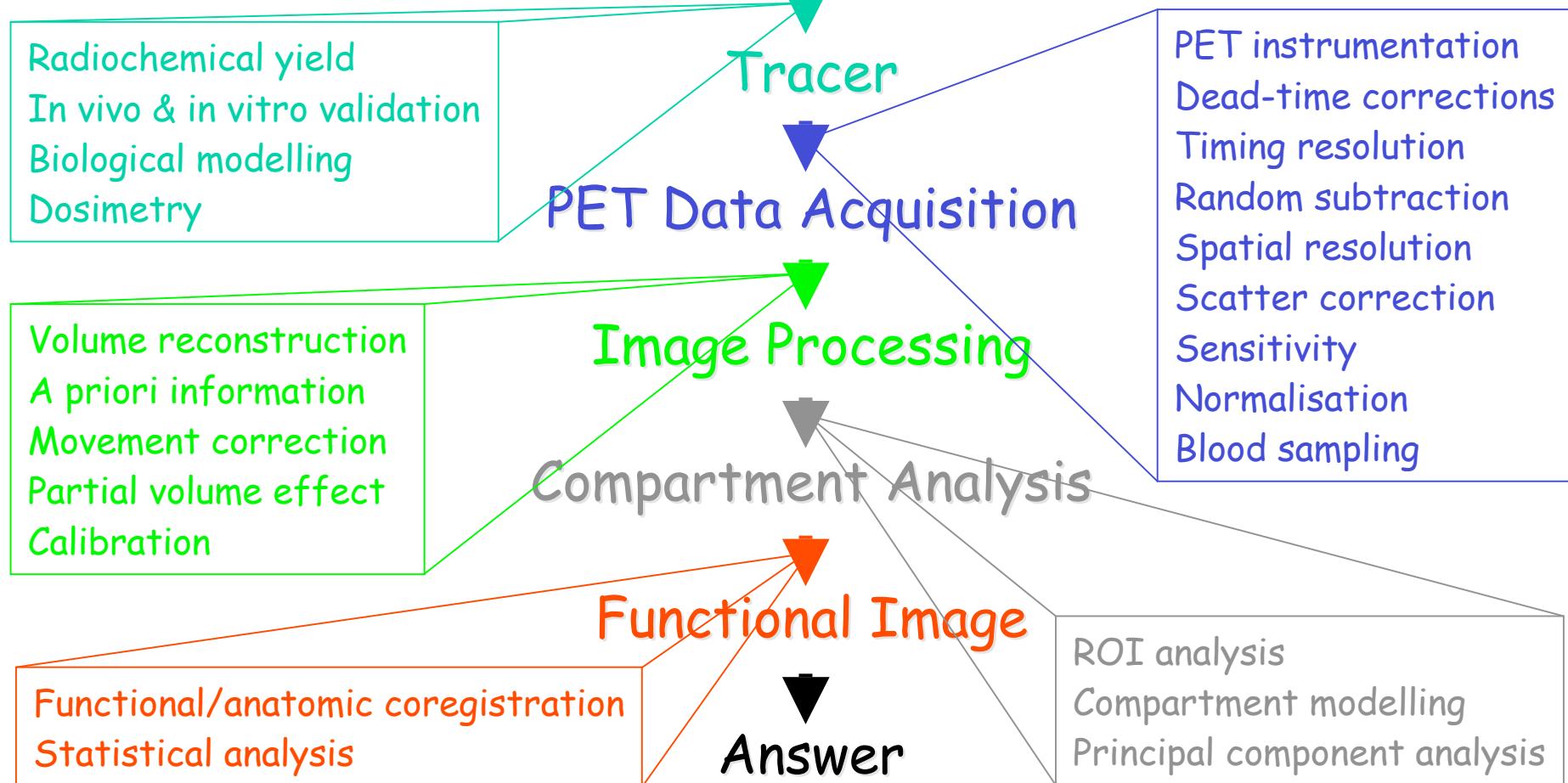
$$C_I^* = C_E^* + C_M^*$$

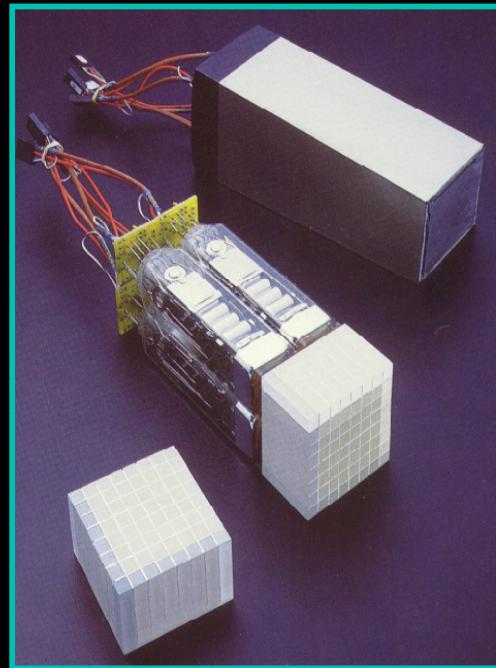


# Biomolecular chemical question

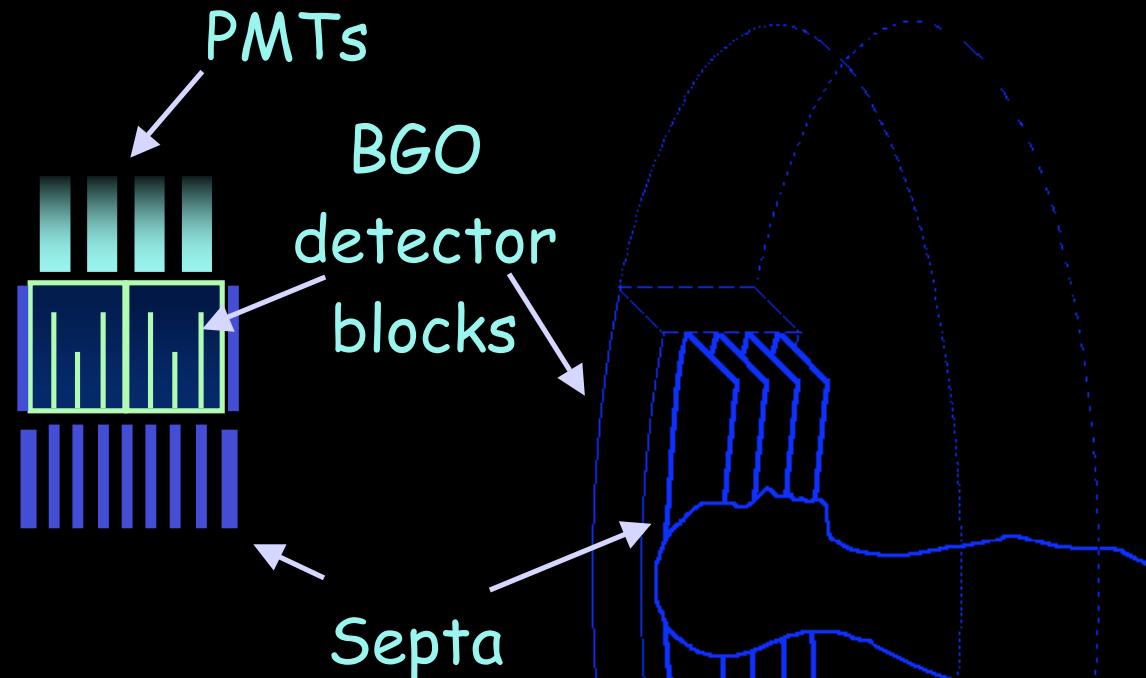


## Pharmacokinetic Pathway & Molecular Target





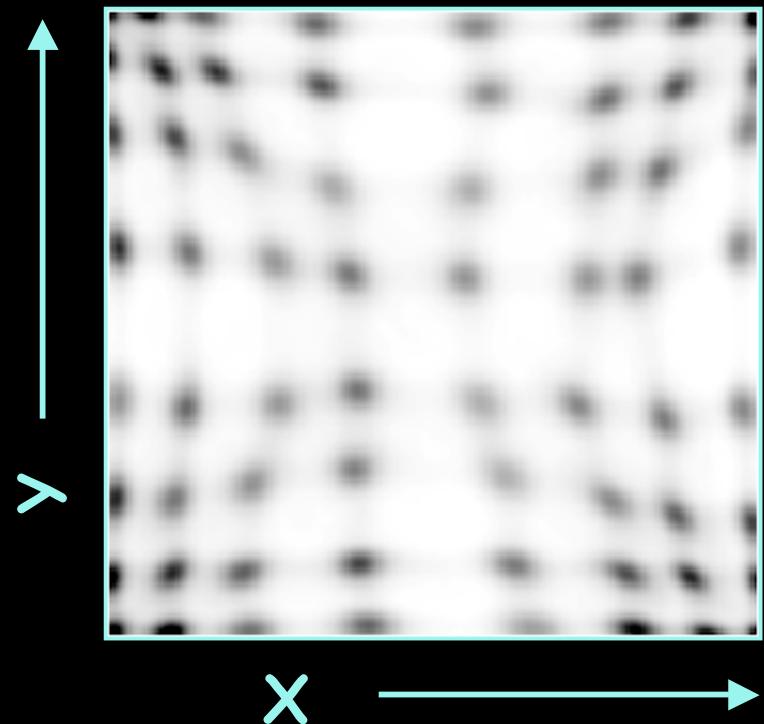
Block detectors



Multi-ring PET scanner with septa

courtesy: D. Townsend, UPMC

# Détecteur bloc: principe de localisation spatiale



$$X = \frac{(D + B) - (C + A)}{\Sigma}$$

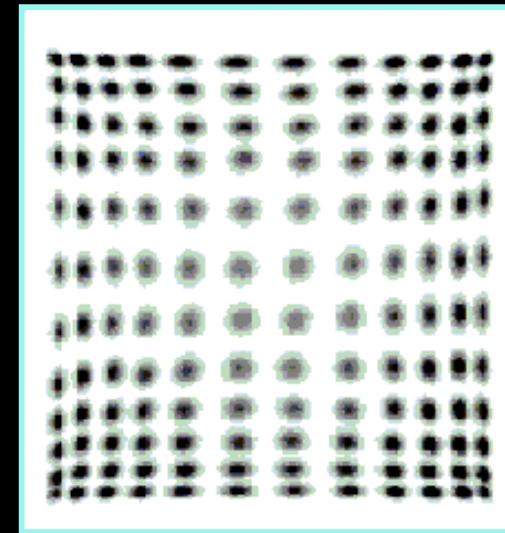
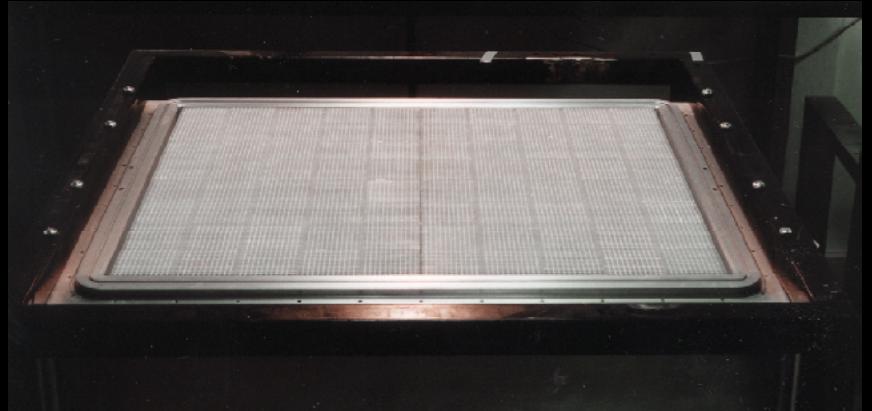
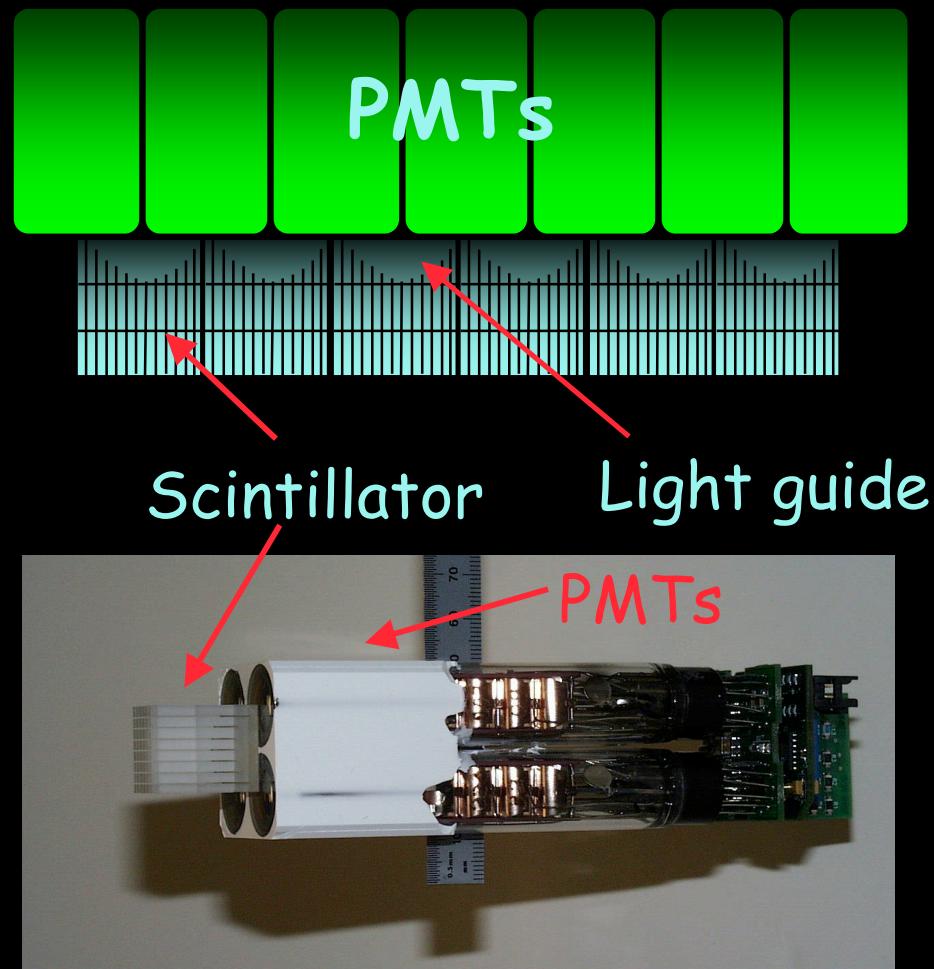
$$Y = \frac{(A + B) - (C + D)}{\Sigma}$$

$$\Sigma = A + B + C + D$$

where LLD <  $\Sigma$  < ULD

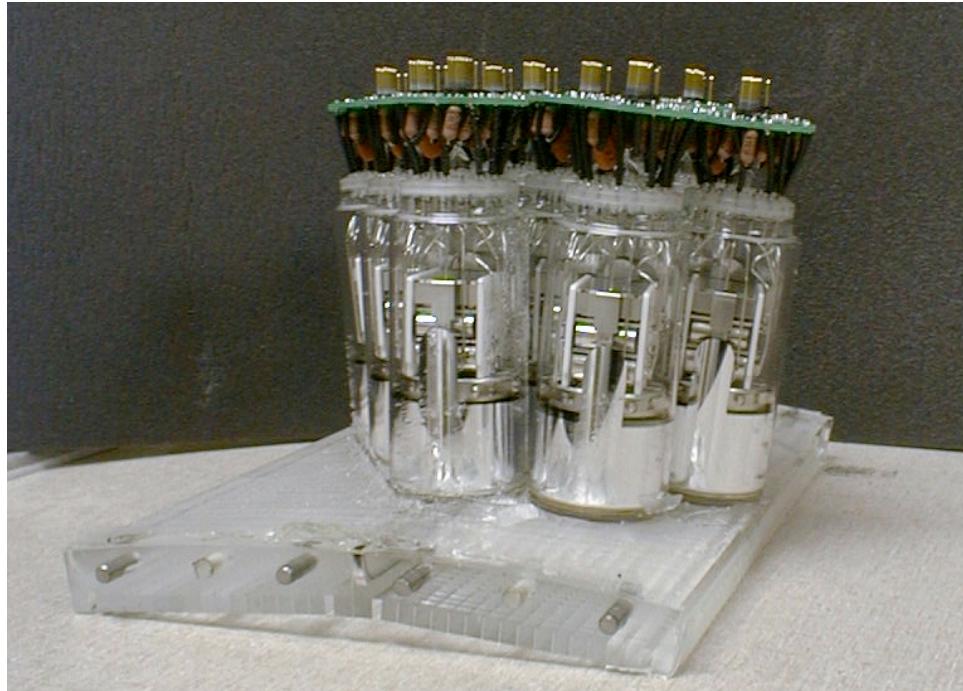
courtesy: D. Townsend, UPMC

# Quadrant sharing panels



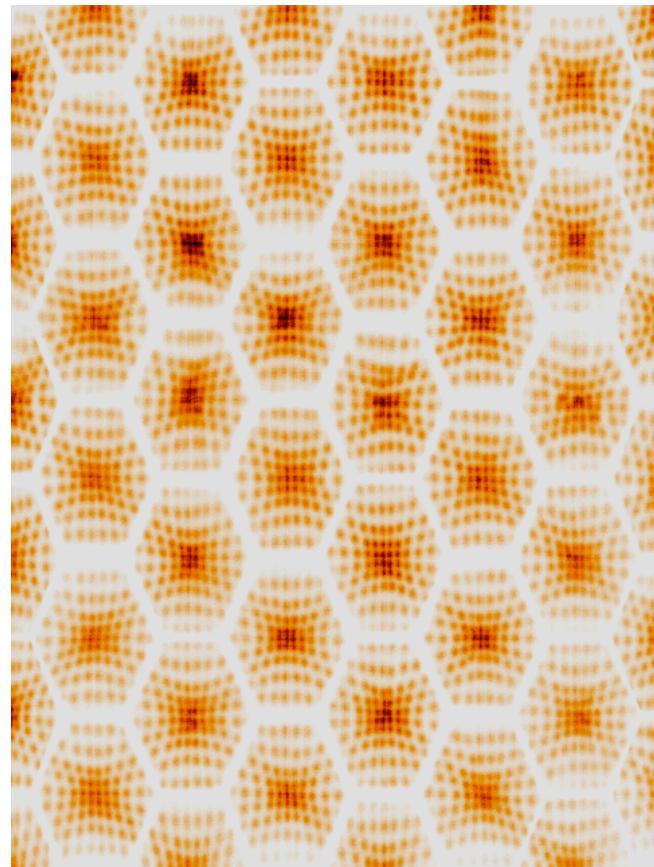
courtesy: D. Townsend, UPMC

# Détecteur pixellisé continu



courtesy: J. Karp, U Penn

# Détecteur pixellisé continu

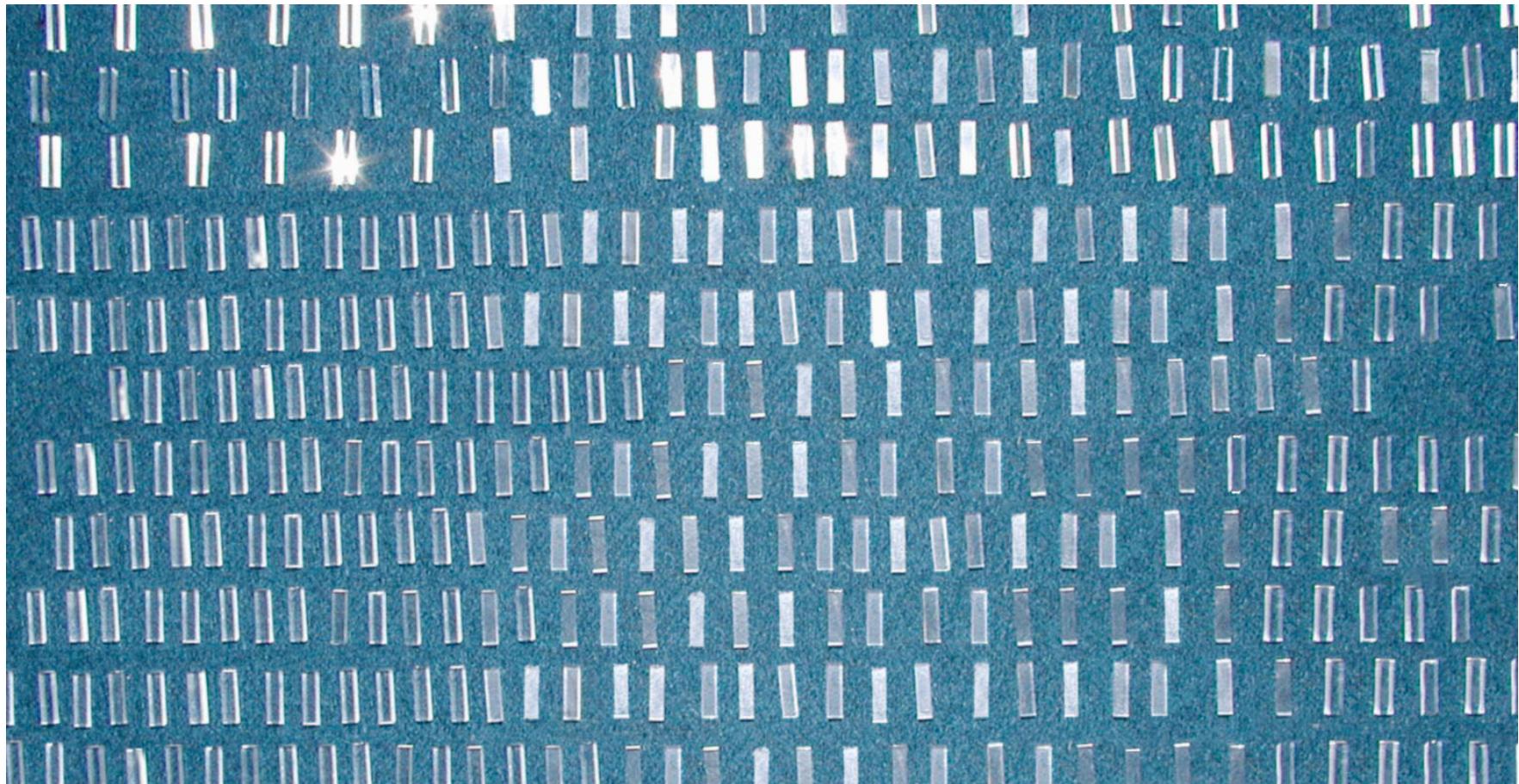


courtesy: J. Karp, U Penn

# Scintillateurs inorganiques utilisés en TEP

	NaI	BGO	GSO:Ce	LSO:Ce	LuAP:Ce
Density (g/cm <sup>3</sup> )	3.67	7.13	6.71	7.40	8.34
Atomic number	51	75	59	66	65
Photofraction	0.17	0.35	0.25	0.32	0.30
Decay time (ns)	230	300	30-60	35-45	17
Light output (hv/MeV)	43000	8200	12500	27000	11400
Peak emission (nm)	415	480	430	420	365
Refraction index	1.85	2.15	1.85	1.82	1.97

# Croissance de cristaux mixtes de LuYAP:Ce



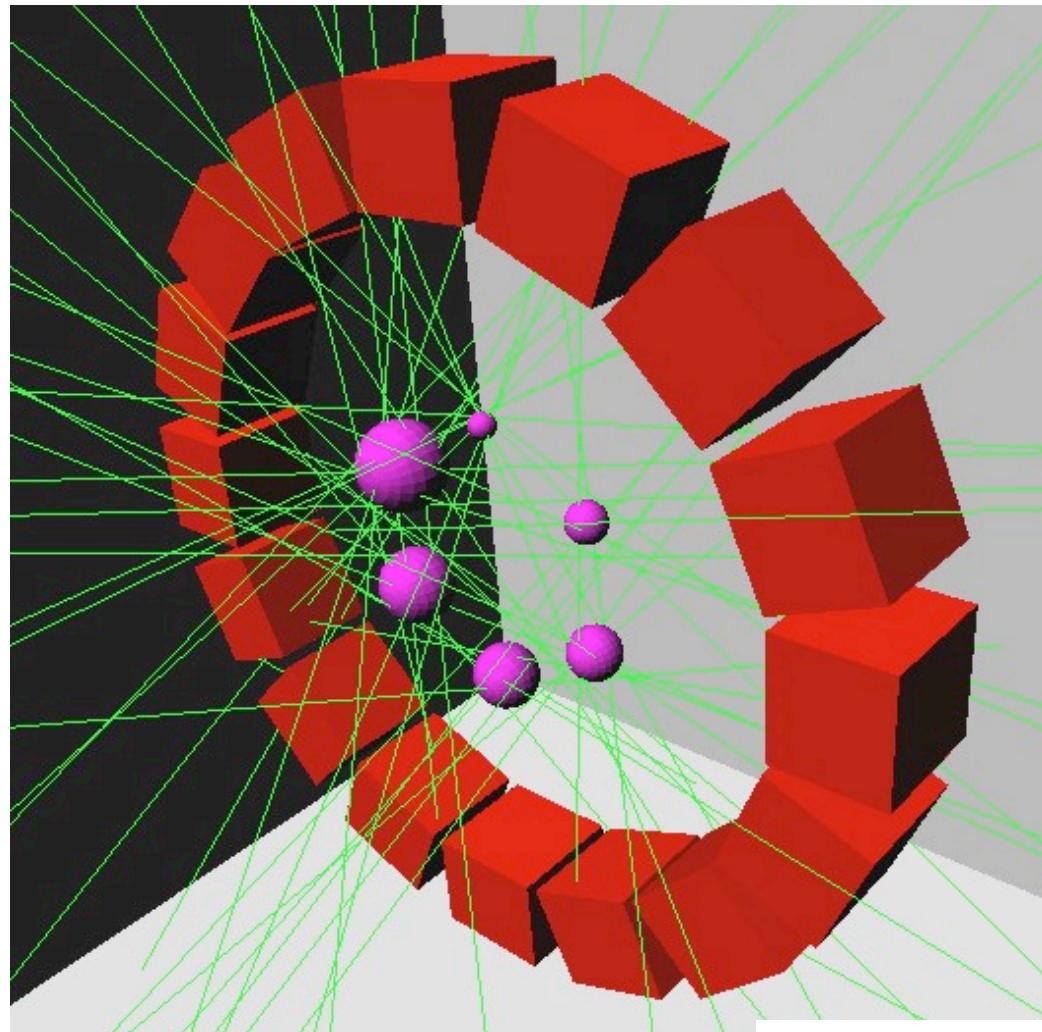
Collaboration Crystal Clear, CERN



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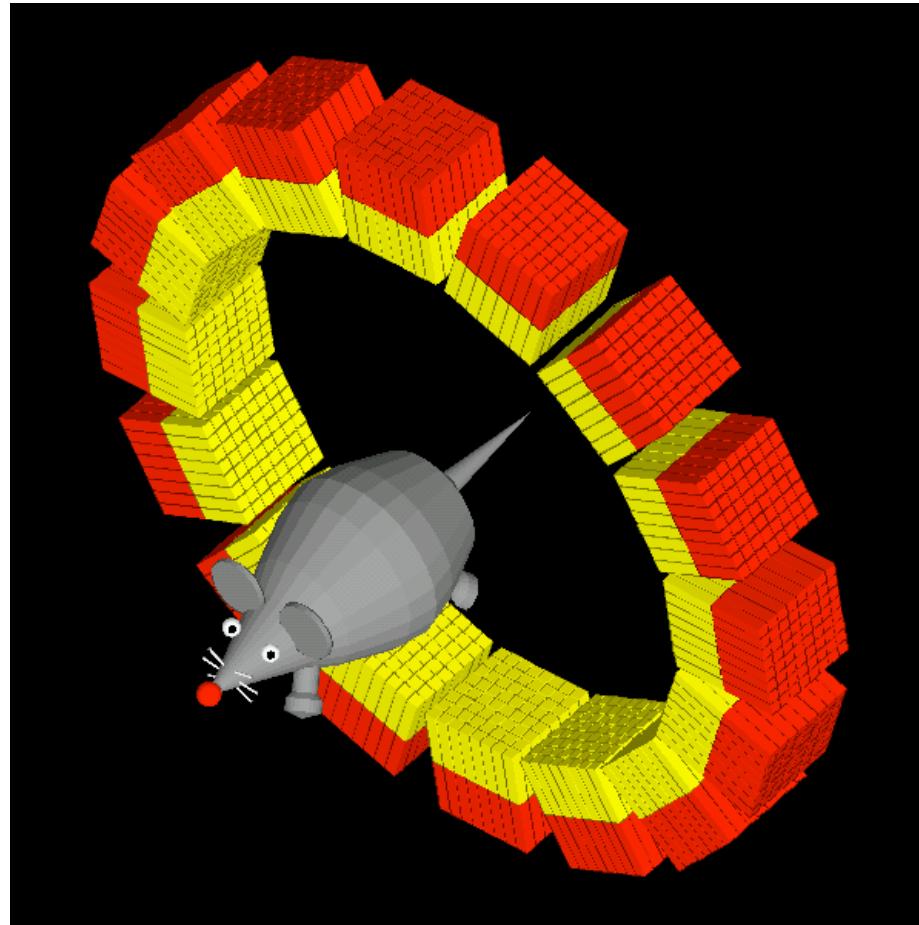


# Simulation par la méthode de Monte Carlo

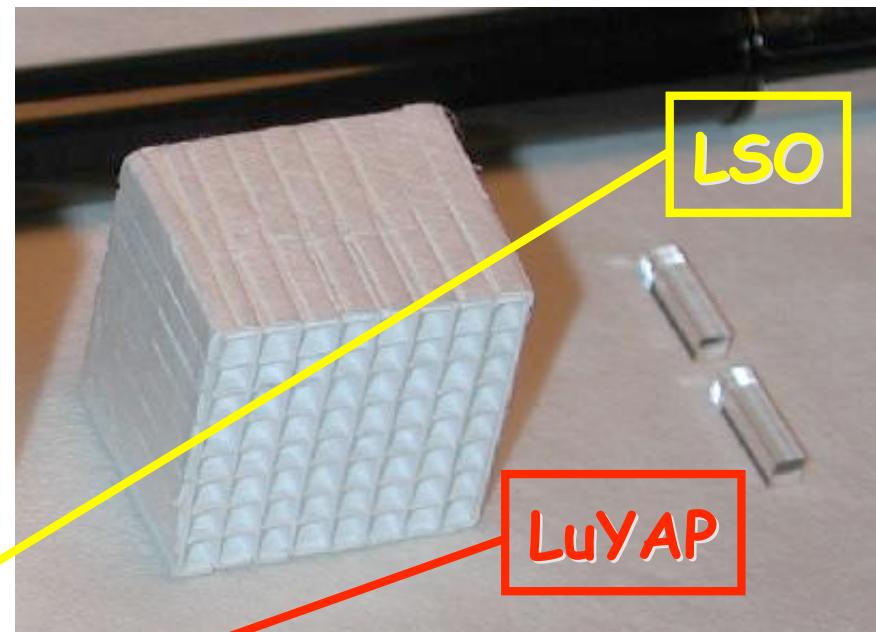
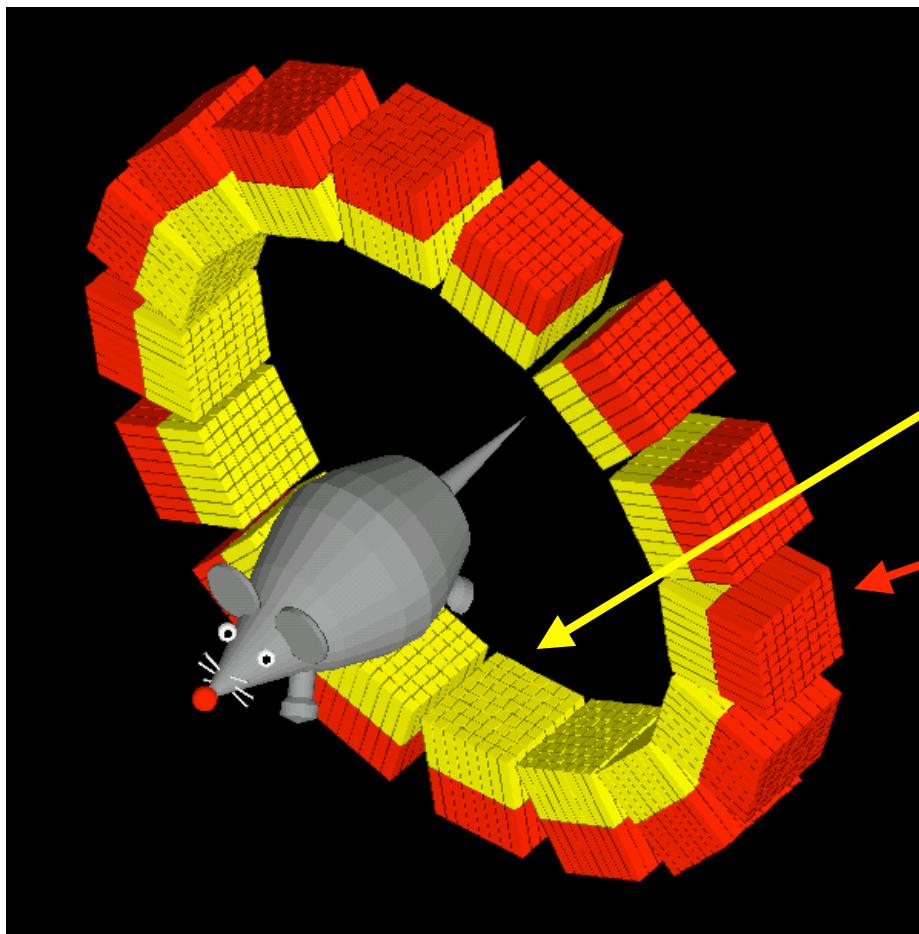


# GATE : Geant4 Application for Tomographic Emission

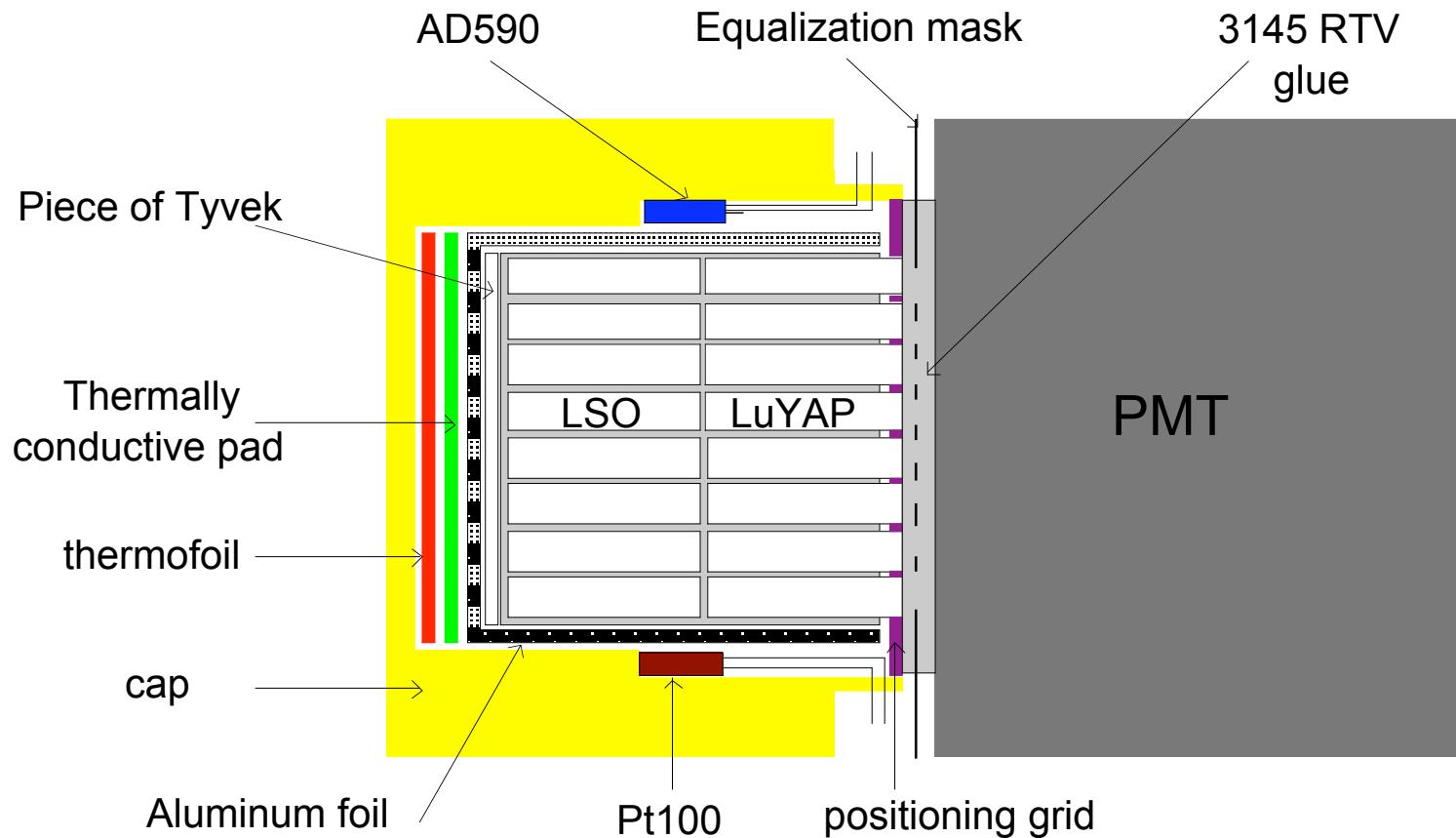
- Particularités de GATE :
- ✓ modélisation du temps
  - ↳ *cinétiques de décroissance, mouvements, fortuits...*
- ✓ facilité, interactivité
  - ↳ *utilisation d'un script*
- ✓ versatilité
  - ↳ *géométrie et simulation totalement scriptées*
- ✓ modularité
  - ↳ *ajout d'extensions facile*
- ✓ développement partagé
  - ↳ *pérénité du logiciel*



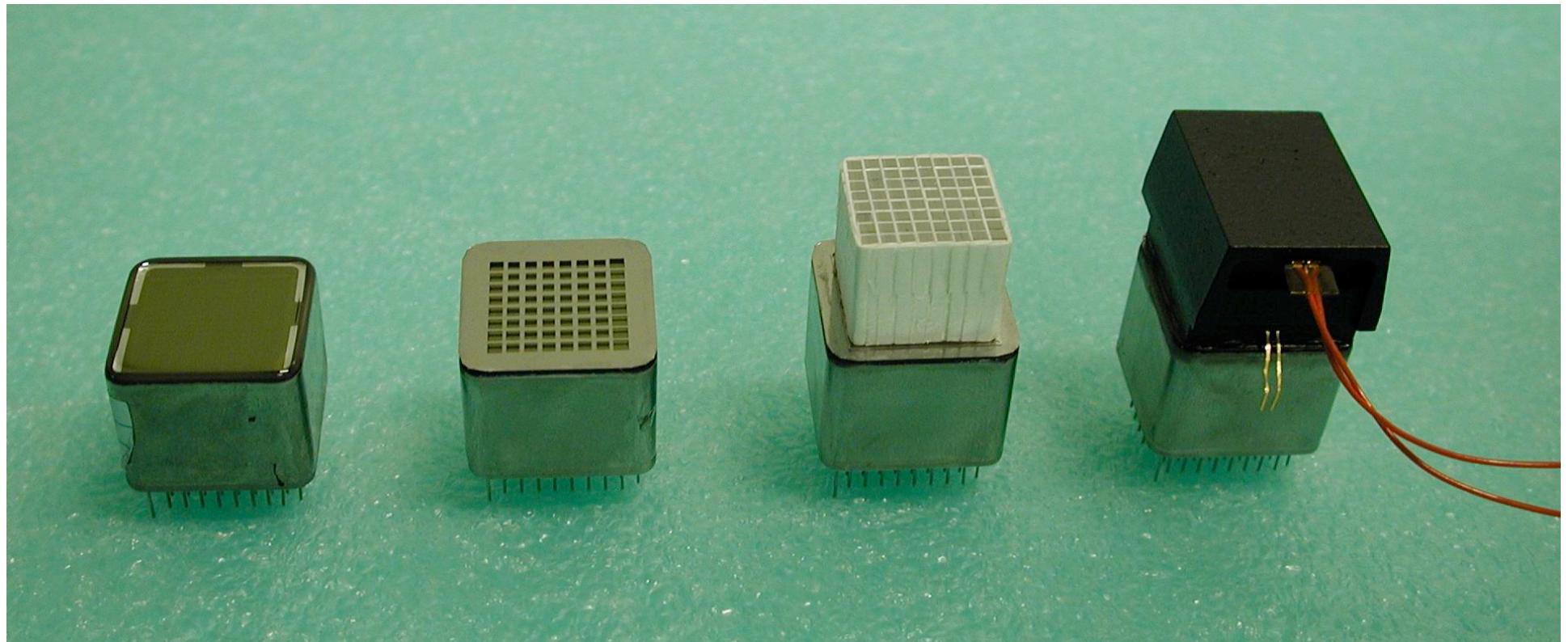
# Module de détection phoswich LSO/LuYAP



# Design du module de détection



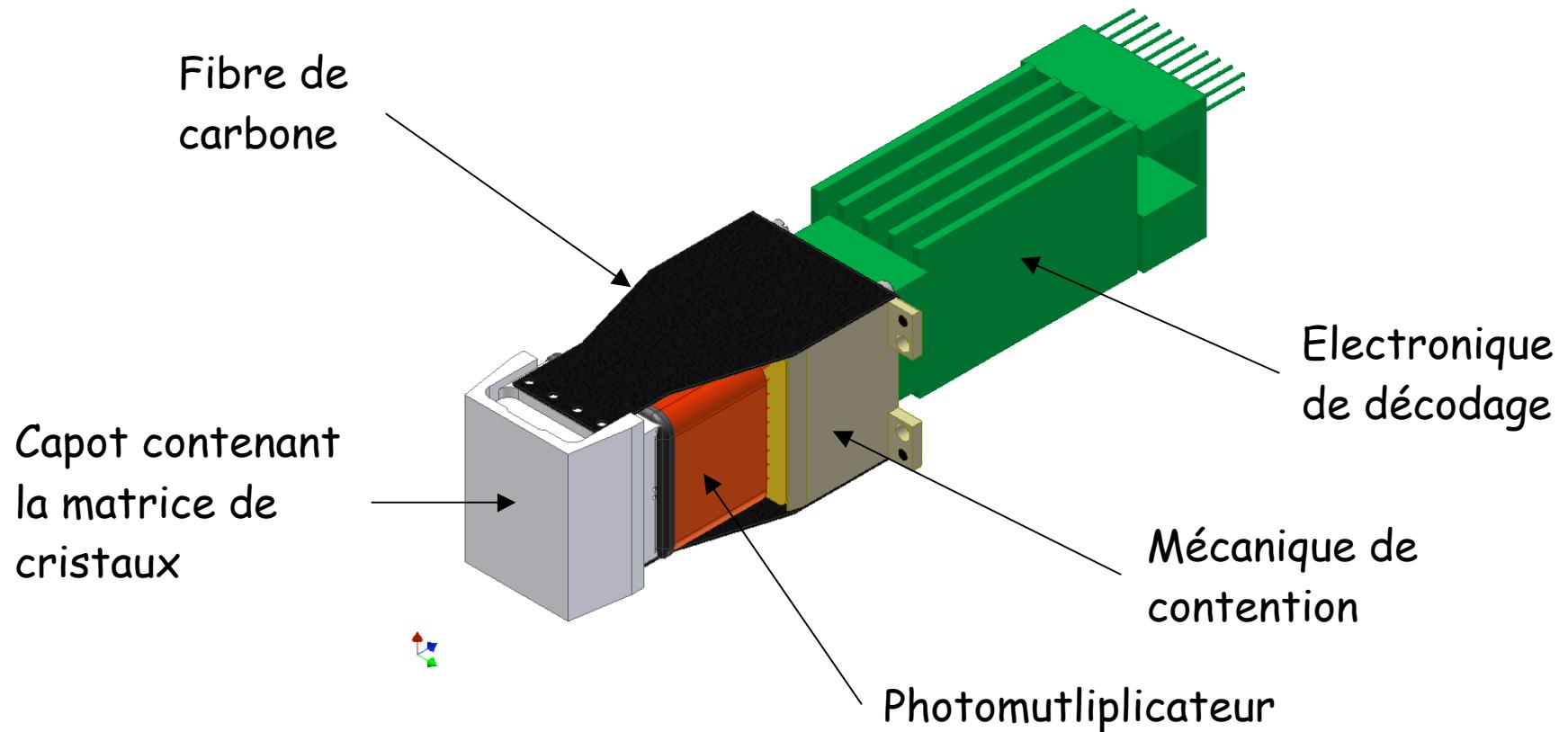
# Design du module de détection



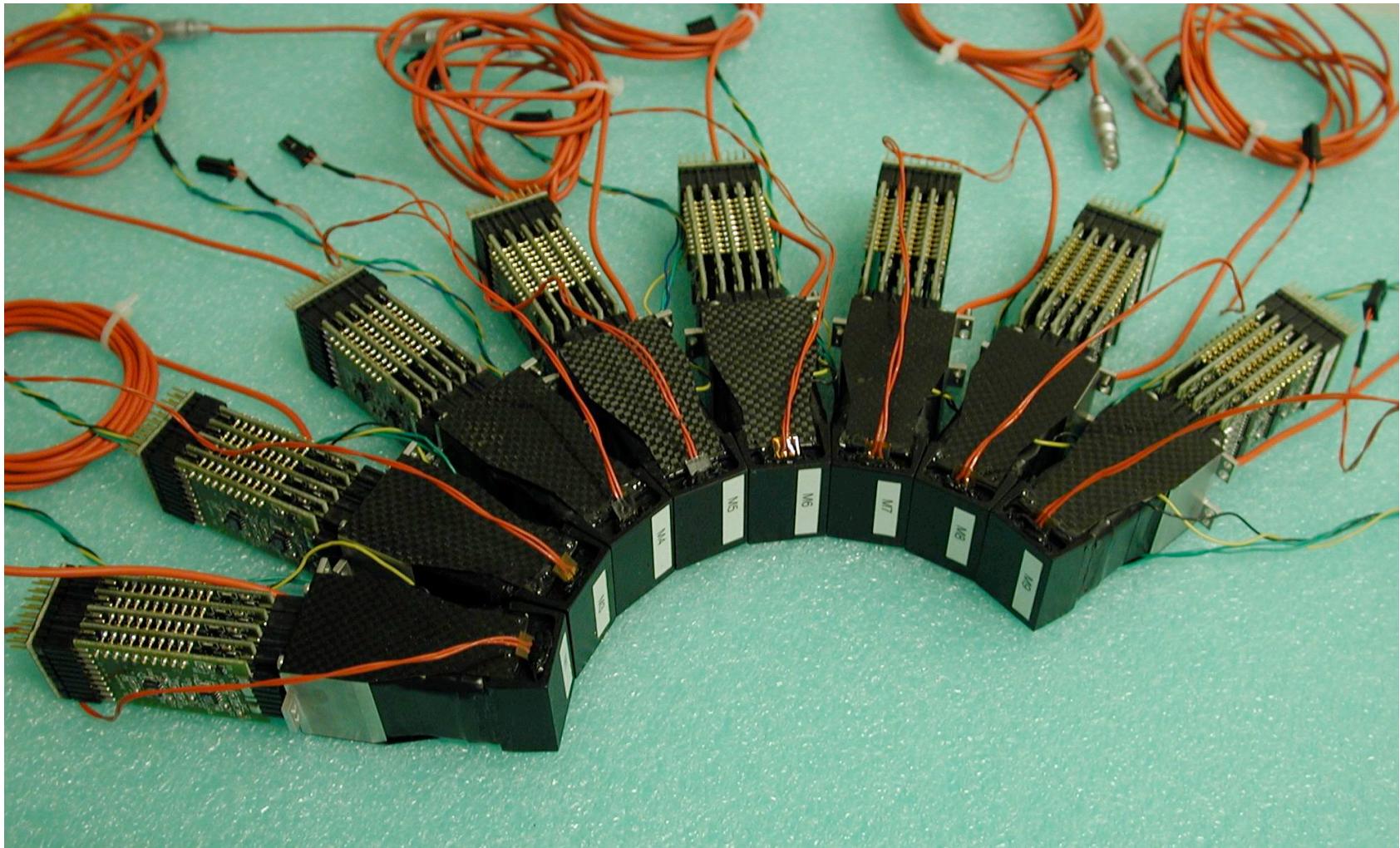
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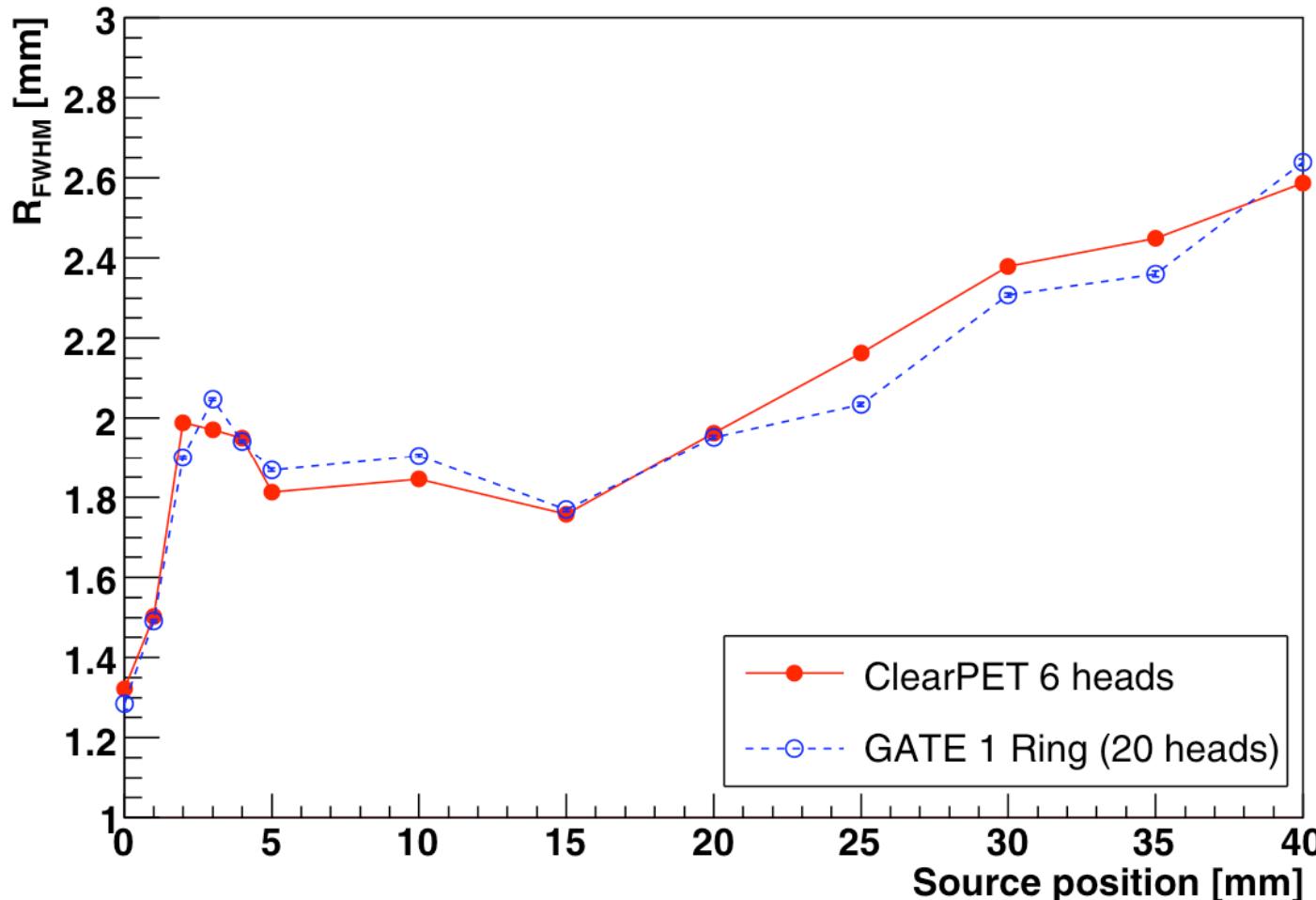
# Design du module de détection



# Design du module de détection



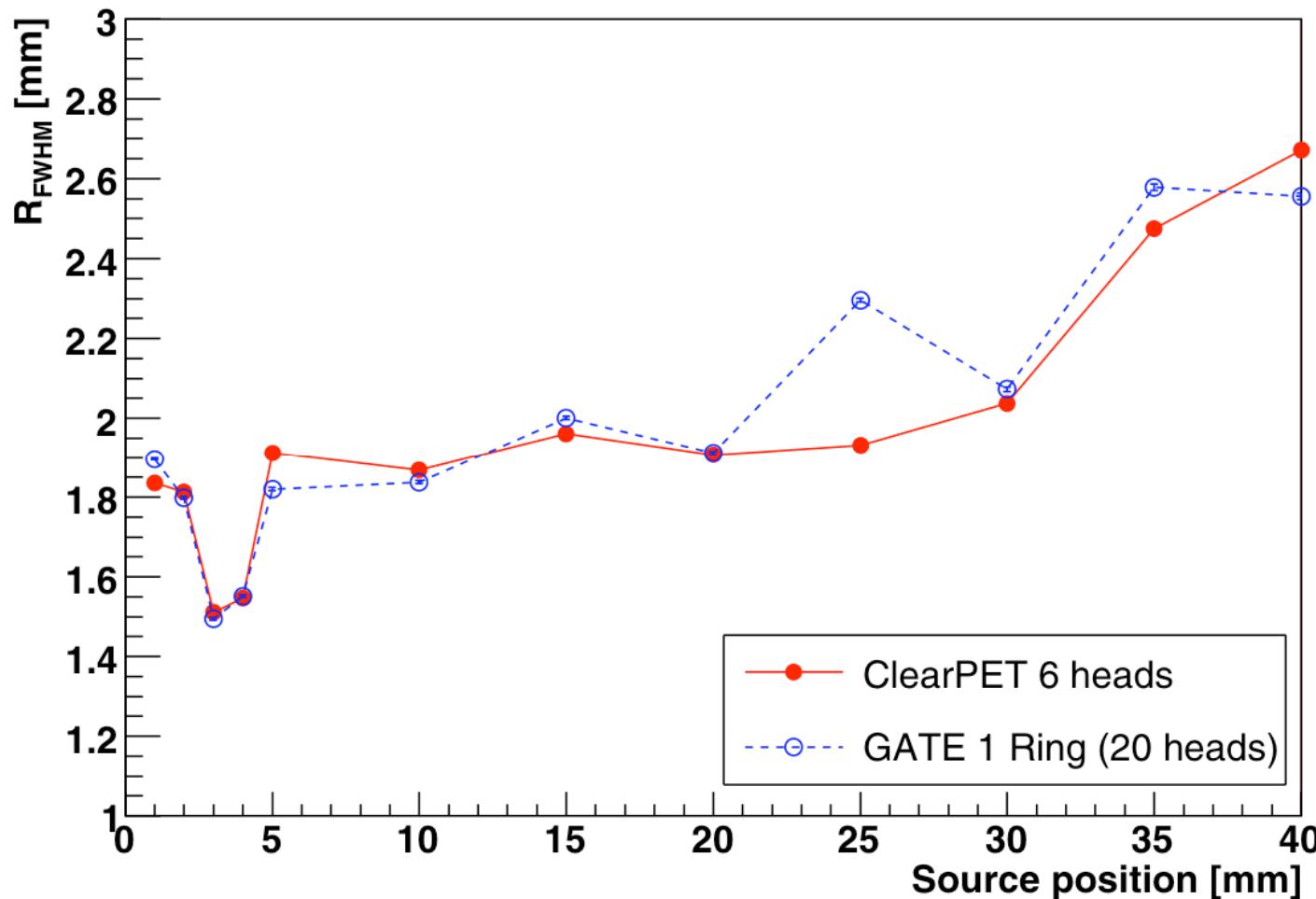
# Comparaison des résolutions radiales expérimentales et simulées



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# Comparaison des résolutions tangentielles expérimentales et simulées



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